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THE ENGINEERING FOUNDATION

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REPORT FOR THE YEAR ENDED FEBRUARY 8, 1923

EIGHTH YEAR

1922/23

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ENGINEERING SOCIETIES BUILDING
NEW YORK CITY
APRIL, 1923

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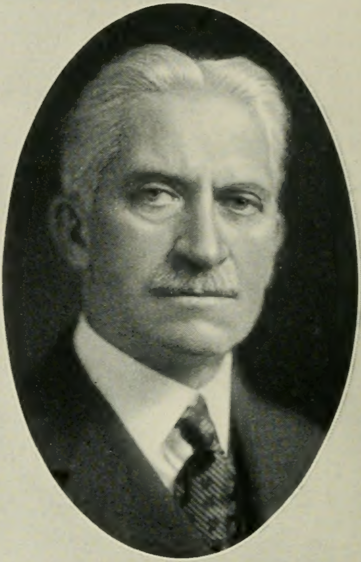
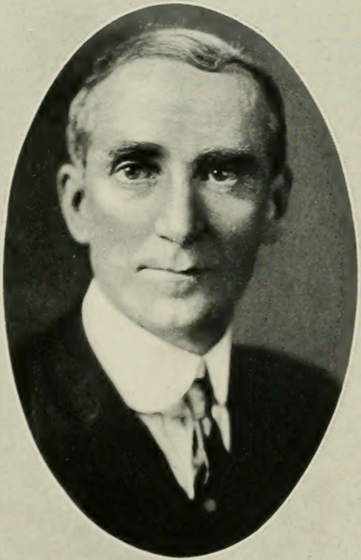
JOHN R. FREEMAN

President, American Society of Civil Engineers



ARTHUR S. DWIGHT

President, American Institute of Mining and Metallurgical Engineers



DEXTER S. KIMBALL

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President, American Institute of Electrical Engineers

THE
ENGINEERING FOUNDATION

JOINT RESEARCH INSTRUMENTALITY OF
AMERICAN SOCIETY OF CIVIL ENGINEERS
AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS
AMERICAN SOCIETY OF MECHANICAL ENGINEERS
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
UNITED ENGINEERING SOCIETY

ANNUAL REPORT FOR EIGHTH YEAR

PUBLICATION
NUMBER 6

ENGINEERING SOCIETIES BUILDING
NEW YORK CITY
APRIL, 1923

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ENGINEERING FOUNDATION: ITS ORIGIN AND FUNCTIONS

Engineering Foundation was established in 1914 by the American societies of Civil, Mining, Mechanical and Electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering, and the good of mankind." It was based upon the vision of Ambrose Swasey, of Cleveland, Ohio, a gift by him, subsequently increased, intended to be the nucleus of a great endowment from many donors, and the mental resources of its Founder Societies.

This endowment and other properties are administered by United Engineering Society, incorporated in New York, May 11, 1904, as trustee of the societies named. Engineering Foundation is a department of United Engineering Society and has discretionary power in the disposition of the income from the endowment and of other funds for current expenditure.

Research is concentrated, directed endeavor to gain knowledge new to the searcher. Research is effort to advance the frontiers of science into the wilderness of the unknown. Each advance in science and in engineering has increased the probability and the possibility of other advances. Engineers are concerned particularly with those researches and investigations in the natural sciences and their applications which have for objectives the sustenance, the convenience, the comfort and the edification of mankind.

Some specific functions of Engineering Foundation are:

Organizing, administering, and aiding cooperative researches and investigations;

Making results of research and investigation available to engineers and industry;

Supporting selected researches and investigations, particularly those expected to yield information of general benefit, but of such nature as not likely to be undertaken by an industrial, a governmental or a private laboratory, separately, with its own resources;

Furthering interest in scientific and technical research.

Engineering Foundation's scope embraces the human as well as the material elements of engineering. The Foundation is a liaison between engineers and scientists, and between engineers and the industries.

Engineering Foundation is uninfluenced by selfish commercial interest, free from technical bias, untrammeled by social or political considerations. As a joint instrumentality of national engineering societies, for research, investigation and kindred activities, it is an expression of the spirit of progress and service among engineers.

ENGINEERING FOUNDATION

REPORT FOR THE YEAR ENDED FEBRUARY 8, 1923

EIGHTH YEAR

EIGHT years of beginnings, in distant retrospect, will seem but as the sunrise of a summer day, in the existence of a great institution founded to seek truth and apply it to "the advancement of the profession of engineering and the good of mankind."

Complexities of modern scientific development are emphasizing to thoughtful minds the unity of truth. Truth has many facets and applications but it is fundamentally a unit. Correspondingly, the fact is being more generally apprehended that research, the seeking for truth, cannot be dismembered into pure and industrial, or fundamental and engineering. Differences in magnitude and technique there may be, but principles remain the same. There are many research tasks and many workers, and each worker sees but a portion of the great field. Results of research in any branch of science may, however, be of value in other branches and in such a variety of arts or technologies as could not have been anticipated when the discoveries were made. Appreciation of research grows among engineers, industrialists and business men, although there are many yet who are uninformed or unconvinced. That research pays in many ways and that support of research is necessary to the prosperity and the continued existence of civilized peoples, is being perceived even by persons remote from laboratories. The choice is between research and retrogression.

In eight years, Engineering Foundation has through breadth of cooperation contributed increasingly to this progress in the appreciation of research and has aided in specific achievements. At the end of 1922, the Foundation was more widely known, not only in engineering and scientific circles, but also to the public, than a year before. Engineering societies through their publications have helped as have the newspapers and the technical and lay magazines. There has been increased demand for publications of the Foundation, especially for the Research Narratives. Research activity and interest among engineering societies have notably increased in the past few years.

Engineering Foundation has faith in its own future and in the profession which it serves. It enters the new year more closely knit with the engineering societies and encouraged by their stimulated interest in research. The field of opportunity is limitless; the will to do exists; work undertaken and done must depend largely upon funds and talents made available. Those who have profited directly by research and engineering should remember their obligations as stewards for the common good. Many engineers and scientists are giving generously of their professional knowledge and skill and of their valuable time.

Summary of the Year

An investigation of arch dams desired by engineers of the far West was organized. Preliminary examination of a proposal for an experimental study of reinforced concrete multiple arch bridges has developed into a project for a study of concrete arches by the American Society of Civil Engineers. The Fatigue of Metals Research has progressed and support for extensions has been assured; the value of results already gotten is widely recognized. The Paint-on-Wood Research, now styled the Investigation of Wood Finishing Processes, is under way in the initial stages.

With National Research Council relations were more intimate than in the preceding year. Not only did Engineering Foundation continue its contributions to the support of the Division of Engineering and some of its projects, but its Secretary was also Chairman of this Division and a member of other divisions and of the Executive Board of the Council. Several members of the Foundation Board were also members of the Research Council. Noteworthy among the enterprises of the Division of Engineering have been its projects in highway research, marine piling investigations, welding, molding sands, and hardness testing of materials. There have been frequent exchanges of courtesies with the Research Information Service and other divisions of the Council.

The four stated meetings of the Foundation were held, but no special meetings. The average attendance of members was eleven, or seventy per cent, in addition to members of the staff and guests.

Rules for property accounting were adopted. In the summer, the Secretary visited engineering societies in eleven Western cities. In September the office of Director was created and the Secretary elected thereto. A new by-law providing for such office was adopted by United Engineering Society.

Publications included the Annual Report for 1921 and a Progress Report on Fatigue of Metals Research, a Directory of Hydraulic Laboratories in the United States, and twenty-four Research Narratives.

The financial policy was one of conservation, so that a surplus might be accumulated. A balance slightly larger than a year's income has been carried forward.

Engineering Societies Library and a number of engineering societies have been helpful. Conversely, it has been the privilege of the Foundation to be of assistance in numerous minor ways to individuals, industries and societies, not only in our country, but also in distant lands.

Arch Dam Investigation

THE DESIRE of engineers and owners of water powers in the far West for a scientific investigation of arch dams was expressed in a letter dated March 3, 1922, from Fred A. Noetzli, of San Francisco. Engineering Foundation investigated this proposal through personal inquiries, correspondence and visits of its Secretary to several centers of engineering in the Rocky Mountain and Pacific Coast States. Evidences of interest and support and prospects of useful results were so assuring that the project was undertaken in the early Fall. A committee of limited membership was created and collection of information about existing arch dams begun. On the committee are representatives of the U. S. Reclamation Service, the State of California, the City of San Francisco, the American Society of Civil Engineers and Engineering Foundation. For obvious reasons headquarters were established in San Francisco, the Engineer's Club of that city generously offering hospitalities.

Privileges have been accorded the committee of associating with itself counsellors and sub-committees. As counsellors there may be chosen eminent engineers who can make contributions of knowledge especially valuable to the investigation. To sub-committees will be assigned specific features of the project; membership on sub-committees is not restricted to members of the main committee.

The committee's first meeting, held January 18, 1923, was devoted to organization and preliminary consideration of program. Charles Derleth, Jr., Professor of Civil Engineering and Dean of the College of Civil Engineering, of the University of California, was elected chairman, and Fred A. Noetzli, D.Sc., Chief Engineer, Bissell and Sinnicks, consulting engineers, of San Francisco, was elected Secretary. Sub-committees on Finance, on Program and Instruments, on Publicity and Publication, and on the several existing dams to be examined, were created.

Statements of information were made to the effect that the City of San Francisco, Southern California Edison Company and Pacific Gas and Electric Company would each purchase instruments and make tests at its own expense on its dams in accordance with the committee's program; that the companies would aid in financing a special test dam; that $30,000 had been provided in the draft of the 1923-24 budget of the State of California for an investigation of dams in cooperation with Engineering Foundation. San Joaquin Light & Power Corporation also is cooperating. U. S. Bureau of Standards, U. S. Reclamation Service and instrument makers have aided in determining the most suitable instruments for the investigation.

Numerous masonry dams, especially of concrete, have been curved so as to resemble an arch in shape, but many of them have been of such dimensions as to benefit little if at all from arch action. Many others depend largely upon the arch principle for stability, but even among them there is much variation in dimension and detail of form. The purposes of the investigation are, first, to collect all possible information regarding design, construction, history and behavior of existing arch dams, and, second, to study by observation of existing dams or those to be built in the near future, or of test dams, the movements under changes of load (depth of water in reservoir, etc.), temperature and other conditions.

Fatigue of Metals

Operations have continued at the Engineering Experiment Station of the University of Illinois under the supervision of Professor H. F. Moore, with the counsel of the Advisory Committee of the Division of Engineering of the National Research Council, Dean M. S. Ketchum, of the College of Engineering, and Professor A. N. Talbot, in charge of theoretical and applied mechanics, being the executive representatives of the University. Work under the original agreement with the General Electric Company was completed and the agreement extended. The University continues its generous contribution of services and facilities. A second progress report in condensed form is an appendix to this annual report.

For more than three years this quest has continued for fundamental reasons for the puzzling failures without warning of machine parts subjected to frequently repeated loadings, of springs, automobile and car axles, crankshafts, elevator and hoist ropes, steel rails. Fatigue, or progressive, failures are not new, but with increased use of high-speed equipment have become more numerous. Many tests were made during the seventy years preceding this investigation and their results are still valuable, but they were insufficient for the needs of today. The outstanding gain so far from the present investigation is the determination that there exists an *endurance limit* under reversed stress as one of the physical characters of wrought ferrous metals, just as there is an ultimate tensile strength. The endurance limit, as defined by Professor Moore, is that stress below which metal can withstand an indefinitely large number of complete reversals of stress. Have all metals an endurance limit? Possibly there are metals which do not possess this character—some of the non-ferrous group, such as some of the copper alloys, for example? This question has been raised. What is its significance as to certain uses of these alloys in the arts?

"This investigation has not *discovered* the endurance limit," according to Professor Moore, "but has given it a reasonably firm basis as a most significant property for a metal which must withstand repeated stress." Repeated stresses occur in many places where they are unsuspected, due to causes not at first apprehended,—incidental bendings oft recurring, frequent moderate temperature changes in highly stressed objects.

Of great importance to users of high-speed machinery is the detection by non-destructive means of the start of fatigue, or progressive, failures. A railway car axle or the crankshaft of an engine has been in service five years: How can one determine whether there exist in it those minute cracks which are the forerunners of a break? Various methods have been proposed, but this field of inquiry is almost unworked. Much yet remains to be learned about the fatigue phenomena of metals in general, particularly about non-ferrous metals and castings of iron or steel. The results already made public have been widely commended. The General Electric Company has expressed high satisfaction with the quality and economy of work done for it, the results of which are being contributed to the general stock of information.

Fatigue phenomena investigations are being carried on also in the Naval laboratories at Annapolis and in a few laboratories in the industries. So far as has been learned, these investigations are not duplicating, but supplementing and confirming, this cooperative project. The continuance of the experienced test party, the Advisory Committee of experts, and the special equipment, assure a quality and volume of results at low cost which would not soon again be possible, if the present combination were disintegrated before the major task can be completed. Industries to be benefited should, however, bear a share of the cost, if they would have the valuable information which it seems possible to obtain.

Reinforced Concrete Multiple Arches

Bridges are required for many places too wide for a single arch or truss. In some places the height of the bridge also is necessarily great, demanding tall piers to support the arches or trusses. For highway bridges particularly arches and piers of relatively slender dimensions are sufficient in some cases, if cement concrete reinforced with steel be the material. Since the arches and piers of such multiple-arch bridges are tied together, in the usual type of construction, the structure acts as a unit, or as an elastic system. The nature of the structure, therefore, introduces conditions which do not exist in single arches, and gives rise to obscure problems in design.

Paucity of data from experiments or observations on existing bridges with which to confirm or correct the theories used in design led A. C. Janni, an authority on the subject, to propose to Engineering Foundation, a year ago, a thorough investigation which should include the designing, erecting and testing of an experimental structure. With the aid of the Advisory Board on Civil Engineering Research, of the National Research Council, this proposal has been carefully examined. The difficulties are large. The Advisory Board (which includes the Research Committee of the American Society of Civil Engineers) has recommended that a Committee on Concrete and Reinforced Concrete Arches be constituted. The Bureau of Standards, Washington, has offered to cooperate.

Wood-Finishing Investigation

Formerly known as the Investigation of Paint-on-Wood, this project has progressed moderately during the year. Work done has been mostly educational and preparatory. The committee has been organized and has established headquarters in Chicago, in the offices of the national Association of Wood Using Industries. The secretary of the Association, William B. Baker, is also secretary of the committee. Effects of the business depression have retarded financing. Nevertheless, some experimental work has been done in the industries; interest and support have been broadened. The Forest Products Laboratory, of the Department of Agriculture, and the Bureau of Standards, of the Department of Commerce, each has a technical member of its staff engaged upon study of the literature, collection of data and other preliminary work. The Foundation's special committee has cooperated with the project committee, chiefly through the efforts of Dr. A. H. Sabin, in bringing the subject to the attention of men in governmental departments, railroad offices and the industries.

That the investigation is of real importance to users of paints, varnishes and wood and to manufacturers also is indicated by the following facts. It bears upon the use of wood in buildings, furniture, farm implements, vehicle wheels and bodies, railway cars, and the application of paint, varnish and other coatings and impregnating materials. It involves knowledge of the nature of various kinds of wood. More than $300,000,000 worth of paint and varnish is sold in the United States every year, a large portion of which is applied to wood. The value of the wood thus finished and protected, also runs into hundreds of millions annually. The possibilities of economy to be realized by scientific study are great.

Graphitic Corrosion of Cast Iron

"Graphitic Corrosion," as stated in last year's report, is the name which for lack of a better designation has been given to a form of deterioration of cast iron. It has for many years been known that some iron castings when long in contact with sea-water, were so changed that they could readily be cut with a knife. Recently similar change has been observed in castings buried in soils impregnated with saline, acidulous or alkaline water. Damage and danger result. Failures have occurred from this cause in water, gas and oil pipe lines, parts of vessels and other objects. An appendix contains a full report.

INTERNAL STRESSES IN METALS

So GREAT is the desirability of learning how to determine and measure internal stresses in metal parts of machines or of structures, without injury to the parts, that the research begun last year has been continued in a very modest way. Suggestions made by E. P. Polushkin, formerly Chief Inspector in the United States, of the Russian Artillery Commission, and of the Russian Mission of Ways of Communication, appeared worthy of a small-scale research, at least. Work has been continued, therefore, in the metallurgical laboratories of the Columbia School of Mines, under the general supervision of Dr. Arthur L. Walker. The purpose is: first, to find out whether any difference exists in propagation of mechanical vibrations in the strained metal in directions parallel to stresses and perpendicular to them; and, second, to determine whether this difference can be used as a basis for detection and measurement of internal stresses. Several modifications of delicate apparatus have been devised and made in endeavors to overcome experimental difficulties encountered. The difficulties are great, but it is possible that experiments along these lines may yield some useful results. Further information is given in an appendix.

PERSONNEL RESEARCH FEDERATION

THIS FEDERATION, for the "correlation of research activities pertaining to personnel in industry, commerce, education and government wherever such researches are conducted in the spirit and with the methods of science," was established in 1921 through the cooperation of National Research Council, Engineering Foundation and other organizations. During the past year the Federation has been publishing the "Journal of Personnel Research" as a medium for reports of studies in various branches of personnel science and practice, for book reviews and for brief statements of current events. The Journal has been well received. For research reports and other treatises too lengthy to be printed in the Journal, a "Personnel Research Series" of monographs and books has been started. The first number, issued in January, 1923, bears the title "Job Analysis and the Curriculum," by E. K. Strong, Jr., and Richard S. Uhrbrock. The Federation's members include associations, universities, Government bureaus, corporations and individuals. Leonard Outhwaite, of Columbia University, has continued as director of the Federation and editor-in-chief of the Journal. Dr. Robert M. Yerkes, of the National Research Council, is chairman of the Federation, and the Director of Engineering Foundation is secretary.

REPRESENTATION ON JOINT RESEARCH ORGANIZATIONS

FOR ADVANCED researches in the Properties of Steam and the Extension of the Steam Table, the American Society of Mechanical Engineers sponsors a cooperative committee, of which George A. Orrok is chairman and on which Engineering Foundation is represented by Dr. D. S. Jacobus. The Foundation has contributed to the funds for this committee. Researches have been proceeding, one at Harvard University, under the direction of Dr. Harvey N. Davis, on the Joule-Thomson Effect, and another at the Massachusetts Institute of Technology under the direction of Dr. Frederick G. Keyes, on the Pressure-Temperature-Volume Relations of Steam. Studies of supersaturation of steam and other researches are under consideration. The committee has been in communication with physicists and engineers in France and England by correspondence and personal visit, and cooperation seems feasible, which will eliminate useless duplication of work. The British Electrical Manufacturers' Association has been interested. Through this Association it is hoped to secure the cooperation of the highest authorities in the field in England.

Rock-Drill Steel Breakage and Heat Treatment are under investigation by the U. S. Bureau of Mines and U. S. Bureau of Standards jointly in cooperation with engineering societies. Engineering Foundation is represented on this committee, of which Benjamin F. Tillson is chairman, by Professor H. M. Boylston, who reports that a paper entitled "A General Review of the Present Status of Drill Steel Breakage and Heat Treatment," by Francis B. Foley, Metallurgist, U. S. Bureau of Mines, Henry S. Burnholz, Metallurgist, U. S. Bureau of Standards, and Charles Y. Clayton, Professor of Metallurgy, Missouri School of Mines and Metallurgy, and Metallurgist of the U. S. Bureau of Standards, and Consulting Metallurgist of the U. S. Bureau of Mines, was prepared for presentation to the Annual Meeting of the American Institute of Mining and Metallurgical Engineers, in February, 1923.

The American Bureau of Welding, Professor C. A. Adams, director, is the advisory board to the American Welding Society and the

Division of Engineering of National Research Council. Dr. D. S. Jacobus represents Engineering Foundation on this bureau. His report of progress is incorporated in the statement of the Division accompanying this report. There has been developed by this Bureau a plan of "regional research," which differs from the ordinary committee work in that the persons taking part all live within a given locality and at no great distance from a common meeting place. The scientific, practical and engineering talent and research facilities needed are obtained locally.

Highways are as ancient as history, but scientific research in connection with highways, transport thereon and the vehicles used therefor, is modern. Such research has been effectively furthered by the Advisory Board on Highway Research, of the National Research Council, on which Engineering Foundation is represented by its Director and to which it has contributed funds annually. Few features of present-day American commerce and industry are so in need of fundamental and comprehensive, as well as detailed study, as is transportation in all its varieties and aspects. These broad considerations are receiving attention from the Advisory Board and its director, Dr. W. K. Hatt, without neglecting such technical details as the tractive resistance of road surfaces and vehicles, or the structural design of roads, or highway traffic analysis. More information can be found on a subsequent page, in the statement of the Division of Engineering.

Miscellaneous Proposals and Activities

Encouragement of Research and Invention was proposed by Dr. Byron E. Eldred. His plan may be summarized as follows: Establish a department for assisting inventors by (*a*) giving information, advice and financial assistance, (*b*) examining suggestions and inventions offered, (*c*) developing ideas believed to be of value, (*d*) securing patents for, and commercializing inventions which have passed thorough examination; this department to have an engineer director, a staff, a board of review composed of engineers, scientists and patent attorneys, and to be endowed. After careful consideration a special committee reported that this project was outside the field of Engineering Foundation and the Board so decided.

Engineering Encyclopedia may be permitted as an insufficient designation for a plan proposed by Silas H. Woodard, member of Engineering Foundation, for the collection of new information from time to time relating to research and development in the various branches of engineering and publication in very condensed form in the *"Transactions"* of the societies. The purpose is to provide a place where new engineering data, useful in design, construction and operation, can be assembled conveniently for use. A special committee was appointed to study this suggestion. It is under consideration in connection with somewhat related proposals before the engineering societies, Engineering Societies Library Board and National Research Council, particularly the development of engineering abstracts and the establishment of an engineering abstracts journal, possibly as an activity of Engineering Societies Library.

Research Concerning Engineering Organization, a study of principles, necessities and conditions,—not investigations of existing organizations,—was again proposed, this time by the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, and the Western Society of Engineers. Since, however, two of the Founder Societies did not join in the request, and since the expense would be large and funds were not provided, Engineering Foundation decided that the study could not be undertaken, regardless of the merits of the proposal. In 1918, the Foundation offered to make a study, at its own cost, but the offer did not receive unanimous approval of the Societies.

A project for a *National Hydraulic Laboratory*, to be established by the Federal government and devoted to river hydraulics, was endorsed, on request of President Freeman, of the American Society of Civil Engineers, by a letter to Senator Joseph E. Ransdell, sponsor for the joint resolution in the Senate.

A National Engineering Museum was suggested by H. F. J. Porter, Chairman of the Joint Committee of the Delamater-Ericsson Historical Collection, as a project worthy of adoption by Engineering Foundation. The Foundation approved the idea in principle but concluded that to assume control of the project and to become custodian of its funds were functions outside the province of Engineering Foundation.

Railroad Electrification was proposed by E. P. Burch, Fellow, American Institute of Electrical Engineers, of Minneapolis, as a topic worthy of thorough and comprehensive investigation under the auspices of Engineering Foundation. He generously offered his services and large accumulation of data. Inquiry having revealed that this subject was being investigated by large corporations building electrical equipment, that the American Society of Civil Engineers had a committee on the subject and that commercial conditions were such that Engineering Foundation could not make a helpful contribution, it was decided to decline this interesting proposal.

Other Activities

Efforts were continued in quiet ways to advance cordial relations between engineers in the United States and in other countries, through correspondence, furnishing information, sending literature and exchanging visits, in cooperation with the engineering societies. Several engineers who have gone abroad have been accredited as envoys of Engineering Foundation: Dr. A. R. Ledoux to England and France; Calvin W. Rice, Secretary of the American Society of Mechanical Engineers, to Brazil and other countries in South America; Elmer A. Sperry, to Japan.

During the summer, the Secretary made an extended trip through the far West, speaking to groups of engineers in Salt Lake City, Los Angeles, Lompoc, San Francisco, Sacramento, Portland, Seattle, Duluth, Saint Paul, Minneapolis. He also visited Prince Rupert, British Columbia, and other places in connection with the Marine Piling Investigation.

Members of the Board and its Director have addressed other bodies on Engineering Foundation and its work, and several papers on these subjects have been published.

Financial Summary

Financial resources are somewhat greater than ever before. The balance brought forward from 1921 was $12,958.33. The income during the year 1922 was $31,014.21, the total resources, $43,972.54, and the expenditures $16,950.27. A balance of $27,022.27 was carried forward into 1923. Total resources amount to $54,000. During 1922, a policy of conservation was followed so as to accumulate a fund for larger operations. In addition to the sums mentioned, $13,000 was received from the General Electric Company on account of its $30,000 participation in the Fatigue of Metals research. Other amounts were expended by various companies or societies for projects in which the Foundation cooperated, but did not pass through the

Foundation's books. Furthermore, services and supplies of large aggregate value have been contributed by industries, societies, members of the Board, and other individuals.

PUBLICATIONS AND PUBLICITY

PUBLICATION NUMBER 4, containing the report for the Foundation's year ended February 9, 1922, and a report of progress in the research on Fatigue of Metals, was issued in March. In June, Publication Number 5 was put out, being a directory of Hydraulic Laboratories in the United States, listing 49 such laboratories. Information concerning six additional laboratories has since been received. Research Narratives, five-minute stories of research and invention, begun in January, 1921, have been continued in semi-monthly issue. To date, fifty-one Narratives have been mailed to approximately 1,700 prominent men of means, leading executives and engineers in many industries, educators, societies, libraries and journals. The Narratives continue to win commendation and many have been copied, with permission, by daily papers, magazines and technical journals. A complete list of publications is given on a subsequent page.

James T. Grady, Director of the Department of Public Information, of Columbia University, has managed the simple publicity of Engineering Foundation throughout the year, on a modest scale. Generally, the aims of publicity have been: First, to familiarize the country with the character and purposes of the Foundation; second, to promote the idea of research in connection with the industries and the practice of engineering; and, third, to further international engineering unity. The Foundation and the doctrine for which it stands are rapidly entering the realm of common knowledge. During the twelve months just closed the publicity gained both in volume and in exactness of treatment. In one form or another the publicity has found its way through practically the entire range of the public press as well as the technical journals. The Research Narratives have provided a source of abundant material and clipping returns show that stories based on these Narratives course through the nation's press for many months.

ACKNOWLEDGMENTS

ENGINEERING FOUNDATION acknowledges with thanks courtesies from the Founder Societies, including use of rooms for meeting, frequent allotment of space in the reading and the advertising pages of their publications and other acts of cooperation, and particularly the constant aid of their secretaries, John H. Dunlap, of American Society of Civil Engineers, F. F. Sharpless, of American Institute of Mining and Metallurgical Engineers, Calvin W. Rice, of American Society of Mechanical Engineers, and F. L. Hutchinson, of American Institute of Electrical Engineers. Appreciation is expressed for various acts of helpfulness by the Western Society of Engineers, the Engineers' Club of San Francisco and other organizations at a distance from New York. Thanks are extended to persons who have worked on committees and to the eminent engineers and scientists who have so generously contributed the Research Narratives.

Meetings and Organization

Four Regular Meetings were held during the year. In November, Edwin Ludlow resigned and the vacancy was filled by election of Colonel Arthur S. Dwight. There were no other changes in the membership or officers. At its meeting September 14, the Foundation created the office of Director and elected its Secretary to the position with the stipulation that he should devote all his time, excepting that required by the secretaryship of United Engineering Society. Acceptance of this appointment led to resignation of the chairmanship of the Division of Engineering, of National Research Council, effective February 15, 1923. Lists of the members, officers and committees of the Foundation and a financial statement are appended.

Charles F. Rand,
Chairman

Alfred D. Flinn,
Director

DIVISION OF ENGINEERING, NATIONAL RESEARCH COUNCIL

THE YEAR'S PROGRESS

Since Engineering Foundation has been represented on this Division and has contributed to its financial support from its inception, a brief report of progress has been presented each year by the Chairman of the Division for the information of the Foundation. The Division held four dinner meetings at The Engineers' Club, New York, for exchange of experience and ideas and for promotion of acquaintance.

Development of Organization

Fourteen societies have been received into the Division of Engineering, an increase of three, the American Institute of Architects, American Railway Engineering Association and American Society for Steel Treating having been invited during 1922. There are now general advisory boards on research in the broad fields of civil, mining and metallurgical, mechanical, electrical, welding, highway and illuminating engineering and testing of materials. Some of these boards have had meetings; others have not met as there has been no need. Individuals and groups of members of all the boards have given helpful advice as called for in connection with cases arising in the Division's work. Engineering Foundation also has had the benefit of such advice on some of its projects. In September 1922, a pamphlet was published, reporting on the work and personnel of the Division and giving a statement of methods of procedure developed for meetings and the conduct of projects, particularly through the instrumentality of committees. Engineering Foundation cooperated throughout the year.

Work Done

Advisory Board on Highway Research, W. K. Hatt, Director. Established in November, 1920, this Board made notable progress during the past year. It has continued to enjoy the support of the Bureau of Public Roads, the American Association of State Highway Officials, technical societies, trade associations, and Engineering Foundation. In an advisory capacity and as a clearing house, chiefly through the personal activities of its Director, the Board has performed valuable services in many parts of the country to those engaged in highway research and construction, has inspired broader studies of the whole subject of transport, and has carried the message to the faculties and students in the engineering colleges. Some of the specific studies in progress under the general direction of committees of the Board are service tests of different forms of road construction, tractive resistance of roads and vehicles, economics of highways location, and surveys of highway traffic. A census of highway researches in progress was made and a bulletin published showing 486 projects. Attention has been directed to the urgent need for thorough and comprehensive investigation of the broad subject of transport—by highway, railway, water, air—so that the proper functions of highways in commerce and travel may be intelligently determined as bases for location, construction and regulation. Attention is being given to safety on the highway. In this phase of the investigation the psychologist has come to the aid of the engineer.

An interesting and successful annual meeting was held in Washington in November. Dean Arthur N. Johnson, of the University of Maryland, was elected chairman to succeed Dean Anson Marston, of Iowa.

American Bureau of Welding, Professor C. A. Adams, Director. Sustained activity and useful production continued to mark this bureau, due to the energy of the committees, the Director and Secretary Spraragen. Progress cannot be more impressively indicated than by listing the reports, issued chiefly through the publications of the American Welding Society:

Standards for Arc Welding Machines;
Resistance Welding Nomenclature;
Present State of Art of Electro-Percussive Welding;
Present State of Art of Making Welded Rail Joints, compiled by Welded Rail Joint Committee;
Present State of the Art of Butt Welding;
Present State of the Art of Welding Cast Iron, by Gas, Electric and Thermit Methods;

Fusion Tests to Determine the Suitability of Various Material for Welding Purposes,—Progress Report of Specifications for Steel to be Welded Committee;

Electric Arc Welding of Cast Iron. (Results of many tests conducted by Northern New York Section of the American Welding Society);

Standards for Resistance Welding Transformers;

Welding of Oil Storage Tanks by Electric Arc.

As these paragraphs are being written in February, 1923, the Committee on Pressure Vessels in cooperation with the U. S. Bureau of Standards, is completing a report on tests to destruction conducted by the Bureau on forty steel tanks made by various methods of welding. The purpose is to supply the Boiler Code Committee of American Society of Mechanical Engineers with authoritative experimental data on which to base reasonable requirements for unfired pressure vessels. Insurance companies have been keenly interested in these tests. Eight manufacturers of tanks and materials supplied tanks, funds and services in accordance with the committee's program, which involved a total expenditure of $15,000.

The investigation of welding rail joints has entered the stage of active experimental work, under a strong committee having Dr. George K. Burgess, of the U. S. Bureau of Standards, for chairman and E. M. T. Ryder, Way Engineer of the Third Avenue R. R., New York, for vice-chairman. It promises results of great practical benefit to all railways using electric power. The American Electric Railway Engineering Association is sponsor for the project. Funds amounting to $20,000, services, equipment and supplies are being contributed by the American Electric Railway Association and companies connected with it, and manufacturers, also, are cooperating,—a total of twenty-two companies. Progress has been made in the design of a rotary service-testing machine and in standardizing methods of making tests. A progress report has been issued covering the present state of the art and of investigations to be undertaken.

As the result of work during the year the Bureau is better known and is recognized both in this country and abroad as an authoritative body on welding research and standardization. Stenographic and other expenses are paid by the American Welding Society. The part-time service of the Secretary is contributed by National Research Council.

Committee on Fatigue Phenomena of Metals, Professor H. F. Moore, Chairman. Work under the agreement with the General Electric Company was completed and the agreement extended to cover additional problems. A second progress report has been written by Professor Moore, with the assistance of the committee and is expected to appear soon as Bulletin 136 of the Engineering Experiment Station, of the University of Illinois.

Committee on Hardness Testing of Materials, A. E. Bellis, Chairman, is examining and endeavoring to define those characteristics of materials intended to be described by the word "hardness" in specifications and tests. A paper by Dr. H. P. Hollnagel, physicist, in the Thompson Laboratory, of the General Electric Company, was presented at the annual meeting of the American Society for Steel Treating. This paper drew extended and instructive discussion in one of the largest and most interesting sessions of the meeting. The paper and discussion were published in the January issue of the Transactions of the American Society for Steel Treating.

Committee on Molding Sand, R. A. Bull, Chairman, under auspices of the American Foundrymen's Association, has continued its studies through subcommittees on Geological Surveys, on Conservation and Reclamation, and on Standard Methods for Testing. The activities of these sub-committees have been reviewed and correlated by the Executive Committee. Practical benefits are being secured and funds are being sought from the industries for extension of the work.

Marine Piling Investigation, R. T. Betts, Chairman, Col. William G. Atwood, Director, is a noteworthy example of cooperative research. It is a joint project of the Divisions of Engineering, of Biology and Agriculture, and of Chemistry and Chemical Technology. The cooperators include also nine Governmental bureaus, more than a score of railroads, a number of steamship and industrial corporations, several universities, museums, municipal and state departments, technical societies, the Canadian government and railroads, and Engineering Foundation. The President of the United States recently designated Hon. C. H. Huston, Assistant Secretary of Commerce, as the Government's representative on the committee.

This investigation combines fundamental researches in biology, anatomy and chemistry with applications to wood and concrete preservation, protection of structures and reduction of losses from damage by marine borers and deterioration of concrete in and near seawater. More than two hundred field stations for collections of biological, chemical and engineering information have been established and are being maintained with the aid of the cooperators, chiefly the Government and the railroads. These stations are situated at carefully selected points along the Pacific, Gulf and Atlantic coasts of our country, from the Aleutian Islands to Maine, on island possessions in the Pacific, the Atlantic and the Caribbean Sea, and in Panama Canal Zone. Researches in laboratories and museums are in progress. The Chemical Warfare Service, of the Army, has recently undertaken extensive chemical researches, some of a novel character.

Previously existing literature relating to marine boring animals ("pile-worms" and others), wood preservation and concrete in sea-water, is being examined, bibliographies compiled and abstracts made. Much original information also has been gotten since the committee began active work on a national scale in the Spring of 1922. Substantial additions have been made to marine biological science. Numerous lessons useful to owners and engineers of water-front properties have already been learned. Several progress statements have been issued. The San Francisco Marine Piling Committee was organized in 1920 because of damage done in the Bay, by Teredo Navalis, one of the pile-worms. These damages amounted to $20,000,000 during the seasons 1919-21. This committee suggested the larger investigation, has cooperated with the national committee since the establishment of the latter and has issued two valuable annual reports. A third report is being printed.

It is the present opinion of biologists who are studying the problem that such a catastrophe as befell San Francisco might occur in several other ports in the event of some relatively slight change of conditions, not yet understood. But aside from these spectacular, infrequent occurrences, direct and indirect damages running to millions of dollars annually are constantly being suffered on many parts of our coasts from deterioration of concrete and the attacks of several kinds of marine borers.

Progress already made is a basis for reasonable expectation of greatly diminishing the losses indicated and reducing the costs for protection of structures. The Committee's accomplishments and prospects justify the more liberal financial support which it needs in order to complete its tasks with the largest benefits to owners of properties on tidewater.

Illumination and Efficiency. Late in the Fall, the Advisory Board on Illuminating Engineering Research, Dr. E. P. Hyde, Chairman, which is also the Research Committee of the Illuminating Engineering Society, suggested an experimental investigation of the Relation of Quality and Quantity of Illumination to Efficiency in the Industries. The suggestion was well received by the Division and is now having thorough preliminary examination to determine its feasibility, cost and probability of support. Already there have been received indications of genuine interest, and informal offers of funds and cooperation.

On this problem, existing data are few, Dr. Hyde has stated, and have been obtained largely by individuals or under the auspices of companies which may be considered interested parties. The importance of establishing the fact that industries throughout the country can be more efficiently operated through the simple and relatively inexpensive expedient of increasing the illumination intensity is apparent and requires no estimate in seven or eight-place figures to substantiate it. It would be equally valuable to know, if the investigation conduced to this conclusion, that no gain in efficiency may be expected from higher illumination intensities beyond some relatively low maximum value. This would prevent the economic loss which would arise through the propagation of erroneous information.

Other Committees and Projects. The scope of the work done by the Division is further shown by the titles of committees whose projects cannot here be reported in detail, for lack of space. Of these may be mentioned Heat Treatment of Carbon Steel, Neumann Bands (in metals), Deoxidizers (for steel), Uses of Tellurium and Selenium, Electrical Core Losses, Electrical Insulation, Physical Changes in Iron and Steel below the Thermal Critical Range, and Heat Transmission.

The meetings of the Division have been utilized for increasing interest in research among engineers and industrialists and have been well attended. Helpful discussions of projects and informative statements of results have been features of these meetings. Engineering Foundation has good reason for gratification at the results which it has helped to achieve through its contribution of funds and services.

William Spraragen has continued as Secretary of the Division. His ability, devotion and enthusiasm merit commendation. The undersigned was elected to succeed himself as chairman, for the year ending June 30, 1923. In September, 1922, however, Engineering Foundation created the office of Director and elected him thereto. Obligations to the Foundation dating from the beginning of 1918 led to acceptance, including the stipulation of full-time service, and consequent resignation from the chairmanship of the Division. The Foundation designated February 15, 1923, as the date on which the new arrangement shall become effective. Service with the Division has been a high privilege.

ALFRED D. FLINN,
Chairman

New York, February 1, 1923.

FINANCIAL STATEMENT

JANUARY 1 TO DECEMBER 31, 1922

EXPENDITURES

	1922 Jan. 1 to Dec. 31	1921 Jan. 1 to Dec. 31	Budget for 1922	Balance Available Dec. 31 1922
ENGINEERING FOUNDATION EXPENSES:				
Salaries	$4,902.50	$4,910.00	$5,200.00	$297.50
Office expenses	731.57	873.94	700.00	—31.57[1]
Stationery and printing	708.03	471.40	600.00	—108.03[1]
Traveling expenses	136.08	73.77	300.00	163.92
Equipment	49.78	139.15	200.00	150.22
Publications	2,200.15	939.50	3,000.00	799.85
Publicity	1,500.00	2,750.00	1,500.00	0.00
Total	$10,228.11	$10,157.76	$11,500.00	$1,271.89
DIVISION OF ENGINEERING, N. R. C.:				
Salaries	$3,164.00	$6,496.32	$3,300.00	$136.00
Office rent	1,711.16	1,656.00	1,656.00	—55.16[1]
Total	$4,875.16	$8,152.32	$4,956.00	$80.84
Investigation of Arch Dams	....	....	$500.00	$500.00
Highway Research, Advisory Board	$1,000.00	$1,000.00	1,000.00	....
Personnel Research Federation	100.00	100.00	100.00	....
Steam Tables Research	333.33	333.33	333.33	....
Internal Stresses in Metals	414.00	....	700.00	286.00
Total	$1,847.00	$1,433.33	$2,633.00	$786.00
Grand Total	$16,950.27	$19,743.41	$19,089.00	$2,138.73

CASH RECEIPTS AND PAYMENTS

Cash on hand January 1, 1922	$12,958.33
(*including temporary investments*)	
Receipts, January 1 to December 31, 1922	31,014.21
Total	$43,972.54
Payments, January 1 to December 31, 1922	16,950.27
Balance on hand, December 31, 1922	$27,022.27

STATEMENT OF ASSETS

Cash on hand, December 31, 1922	$4,054.52
Petty cash	15.00
U. S. Treas. Certs. 5½% (1924)	9,000.00
U. S. Treas. Certs. 4¾% (1925)	7,035.00
U. S. 3rd Liberty Loan 4¼% (1928)	6,917.75
Total	$27,022.27

JOSEPH STRUTHERS,
Treasurer

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[1] Excess

PAST-CHAIRMEN OF ENGINEERING FOUNDATION

Gano Dunn	April, 1915, to February, 1917
Michael I. Pupin	February, 1917, to February, 1919
W. F. M. Goss	February, 1919, to March, 1920

OFFICERS OF ENGINEERING FOUNDATION FOR 1922

Chairman	Charles F. Rand
First Vice-Chairman	Edward Dean Adams
Second Vice-Chairman	Frank B. Jewett
Treasurer	Joseph Struthers
Assistant Treasurer	Henry A. Lardner
Director	Alfred D. Flinn
Assistant Secretary	By reciprocal arrangement, the Permanent Secretary of National Research Council, Vernon Kellogg

EXECUTIVE COMMITTEE

Charles F. Rand, *Chairman*

Edward Dean Adams
George H. Pegram
Frank B. Jewett
H. Hobart Porter

MEMBERSHIP OF BOARD FOR 1922

FOUNDER AND HONORARY MEMBER

Ambrose Swasey

UNITED ENGINEERING SOCIETY

George H. Pegram
Edwin Ludlow
[1] Arthur S. Dwight
George M. Basford
Bancroft Gherardi

AMERICAN SOCIETY OF CIVIL ENGINEERS

Edward Dean Adams
Silas H. Woodard

AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS

Herbert M. Boylston
Arthur L. Walker

AMERICAN SOCIETY OF MECHANICAL ENGINEERS

John H. Barr
David S. Jacobus

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Frank B. Jewett
E. Wilbur Rice, Jr.

MEMBERS AT LARGE

Elmer A. Sperry
Charles F. Rand
H. Hobart Porter

EX-OFFICIO, AS PRESIDENT OF UNITED ENGINEERING SOCIETY

J. Vipond Davies

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[1] Succeeded Edwin Ludlow, resigned, November, 1922.

COMMITTEES OF ENGINEERING FOUNDATION FOR 1922

HYDRAULIC RESEARCH

J. Waldo Smith
Silas H. Woodard

CONTROL OF PUBLICATION OF REPORTS

Edward Dean Adams

ENDOWMENT INCREASE

Charles F. Rand

WOOD FINISHING RESEARCH

Dr. A. H. Sabin
George H. Pegram
The Director

RELATIONS WITH DIVISION OF ENGINEERING, NATIONAL RESEARCH COUNCIL

George H. Pegram

REPRESENTATIVES OF ENGINEERING FOUNDATION 1922

American Bureau of Welding, D. S. Jacobus

Advisory Board on Rock Drill Steels, Herbert M. Boylston

Steam Table Research, D. S. Jacobus

Committee on Wood Finishing Research, The Director

Personnel Research Federation, The Director

Advisory Board on Highway Research, The Director

OFFICERS OF ENGINEERING FOUNDATION FOR 1923

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Assistant Treasurer	Henry A. Lardner
Director	Alfred D. Flinn
Assistant Secretary	By reciprocal arrangement, the Permanent Secretary of National Research Council, Vernon Kellogg

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Edward Dean Adams   Frank B. Jewett
George H. Pegram   H. Hobart Porter

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FOUNDER AND HONORARY MEMBER
Ambrose Swasey

UNITED ENGINEERING SOCIETY
George H. Pegram   W. F. M. Goss
Arthur S. Dwight   Bancroft Gherardi

AMERICAN SOCIETY OF CIVIL ENGINEERS
Edward Dean Adams   Silas H. Woodard

AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS
Herbert M. Boylston   Arthur L. Walker

AMERICAN SOCIETY OF MECHANICAL ENGINEERS
John H. Barr   David S. Jacobus

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
Frank B. Jewett   E. Wilbur Rice, Jr.

MEMBERS AT LARGE
H. Hobart Porter   Charles F. Rand
Elmer A. Sperry

EX-OFFICIO, AS PRESIDENT OF UNITED ENGINEERING SOCIETY
J. Vipond Davies

MEMBER SOCIETIES

AMERICAN SOCIETY OF CIVIL ENGINEERS
Charles F. Loweth, *President*   John H. Dunlap, *Secretary*

AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS
E. P. Mathewson, *President*   F. F. Sharpless, *Secretary*

AMERICAN SOCIETY OF MECHANICAL ENGINEERS
John Lyle Harrington, *President*   Calvin W. Rice, *Secretary*

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
F. B. Jewett, *President*   F. L. Hutchinson, *Secretary*

COMMITTEES OF ENGINEERING FOUNDATION FOR 1923

HYDRAULIC RESEARCH

J. Waldo Smith
Silas H. Woodard

CONTROL OF PUBLICATION OF REPORTS

Edward Dean Adams

ENDOWMENT INCREASE

Charles F. Rand

ARCH DAM INVESTIGATION

C. Derleth, Jr., *Chairman*
Fred A. Noetzli, *Secretary*
H. Hawgood
D. C. Henny
W. F. McClure[1]
M. M. O'Shaughnessy[2]
H. Hobart Porter[3]
F. E. Weymouth
Silas H. Woodard

ALTERNATES: [1] Paul Bailey, [2] R. P. McIntosh, [3] Wynn Meredith

WOOD FINISHING RESEARCH

Dr. A. H. Sabin
George H. Pegram
The Director

REPRESENTATIVES OF ENGINEERING FOUNDATION, 1923

AMERICAN BUREAU OF WELDING, D. S. Jacobus

ADVISORY BOARD ON ROCK DRILL STEELS, Herbert M. Boylston

STEAM TABLE RESEARCH, D. S. Jacobus

COMMITTEE ON WOOD FINISHING RESEARCH, The Director

PERSONNEL RESEARCH FEDERATION, The Director

ADVISORY BOARD ON HIGHWAY RESEARCH, The Director

FORMS FOR DEED OF GIFT AND BEQUEST

No. 1—Simple General Form for Deed of Gift

The United Engineering Society, a New York corporation, having established a fund known as the Engineering Foundation,

I hereby give to said United Engineering Society the sum of....................

....Dollars ($.................), which shall be invested and reinvested by United Engineering Society and the income thereof used by Engineering Foundation for the furtherance of research in science and engineering or for the advancement in any other manner of the profession of engineering and the good of mankind.

Witness my hand and seal at..this

........................day of..............................19.....

....

(Signature)

In the presence of:

....

No. 2—Form for Deed of Gift with Preference for Specific Purposes

The United Engineering Society, a New York corporation, having established a fund known as the Engineering Foundation,

I hereby give to said United Engineering Society the sum of....................

....Dollars ($..................), which shall be invested and reinvested by United Engineering Society and the income thereof used by Engineering Foundation for the furtherance of research in science and engineering or for the advancement in any other manner of the profession of engineering and the good of mankind. It is, however, my will and desire that so long as may be advisable in the opinion of Engineering Foundation Board, said income or so much thereof as shall by said Board be deemed advisable, shall be used

for the following specific purposes: ....

....

....

Witness my hand and seal at..this

..................day of............................19.....

....

(Signature)

In the presence of:

....

FORM OF BEQUEST

I give to United Engineering Society, a New York corporation, whose principal office is in the City of New York, the sum of............................Dollars ($..............), for the Engineering Foundation maintained by said society.

PUBLICATIONS

1. Report on the Origin, Foundation and Scope of the National Research Council, February, 1917.
2. A Progress Report to United Engineering Society, October, 1919.
3. Annual Report for Year ended February 10, 1921.
4. Annual Report for Year ended February 9, 1922, and Report on Fatigue of Metals.
5. Directory of Hydraulic Laboratories in United States, June, 1922.
6. Annual Report for Year ended February 8, 1923.

REPRINTS

1. The Mental Hygiene of Industry, March, 1920; from *Industrial Management*, February, 1920. Out of print.
2. Trade-Unionism and Temperament, April, 1920; from *Industrial Management*, April, 1920. Price, 25 cents.
3. The Modern Specialist in Unrest, June, 1920; from *Industrial Management*, June, 1920. Price, 25 cents.
4. An Improved Form of Weir for Gaging in Open Channels, May, 1920; from American Society of Mechanical Engineers, June, 1920. Out of print.

RESEARCH NARRATIVES

In January, 1921, the semi-monthly publication was begun of a series of leaflets, each containing the story of some research or discovery or notable achievement in science or engineering, briefly told. There have been printed to date:

Number and Title	*Contributor or Source of Information*
1. Isolated Research: Its Handicaps. The Story of Mendelism.	Prof. A. E. Kennelly, Harvard University and Massachusetts Institute of Technology.
2. Fatigue of Metals: A Story of Co-operation.	Prof. H. F. Moore, Engineering Experiment Station, University of Illinois.
3. Utilizing Low-Grade Ores: An Iron Story.	W. G. Swart, Mining and Metallurgical Engineer, Duluth, Minn.
4. Electric Welding: From Lecture Room to Industry.	Dr. Elihu Thomson, Consulting Engineer, General Electric Co., Lynn, Mass.
5. Early Uses of Nickel: The Accidental Element in Research.	A. J. Wadhams, Assistant General Superintendent, International Nickel Company, Bayonne, N. J.
6. An Ammonia Gas Story: A Simple Solution of a Safety Problem.	Prof. Edward F. Miller, Massachusetts Institute of Technology.
7. Making Explosions Beneficial: Research as a Sociological Factor.	H. W. Jordan, Research Chemist, Semet-Solvay Company, Syracuse, N. Y.
8. The Ruggles Orientator: A Device for Ground Training of Aviators.	Captain Lloyd N. Scott, formerly Liaison Officer to Naval Consulting Board and Secretary, War Committee of Technical Societies.
9. The Centrifugal Creamer: From Laboratory to Factory and Farm.	Dr. Elihu Thomson.

Number and Title	*Contributor or Source of Information*
10. Nitrogen: Its Capture and Utilization.	Various sources.
11. Light in Water: Total Reflection by Animalcules.	Captain Lloyd N. Scott.
12. Thermionics: The Movement of Electricity Under Influence of High Temperature in Vacua.	Dr. D. W. Wilson, Western Electric Company.
13. Radioactivity: New Conceptions of the Constitution of Matter.	Dr. Willis R. Whitney, Director, Research Laboratory, General Electric Company, and Prof. Frederick Soddy on "The Interpretation of Radium and the Structure of the Atom."
14. Wrought Tungsten: A Reward of Many Years Spent in Scientific Research.	Dr. Irving Langmuir, Research Laboratory, General Electric Company.
15. The Gas-Filled Incandescent Lamp: A Product of Continued Search for Higher Efficiency.	Dr. Irving Langmuir.
16. Radium: A Substance so Powerful That One Three-thousand-millionth of a Grain Can Be Identified Easily.	Dr. R. B. Moore, Chief Chemist, United States Bureau of Mines.
17. Helium: One of the Rare Gases of the Atmosphere—Helium, Neon, Argon, Krypton and Xenon.	Dr. R. B. Moore.
18. Direction by Two Ears: Saving Ships by Hearing Magnified Underwater Sounds. Another Example of Results Won by Cooperation.	Dr. Robert A. Millikan, California Institute of Technology.
19. Whittling Iron: Some Irons Are Softened by Saline, Acidulous and Alkaline Waters.	Various sources.
20. Maleic and Fumaric Acids: Discovery of Catalytic Oxidation of Coal Tar Products.	Dr. J. M. Weiss, Manager, Research Department, The Barrett Company.
21. Separating Minerals by Floating: A Metallurgical Process Discovered by a Woman.	Various sources.
22. American Optical Glass: Science Superior to Tradition and Trade Secrets.	Harrison E. Howe, in *The New World of Science*, edited by Dr. Robert M. Yerkes.
23. American Glass for Safety: Achievements of the Collaboration of Science with Industry.	Eugene C. Sullivan, Vice-President, Corning Glass Works.
24. Glassware and Warfare: Industrial Benefits Salvaged from War's Necessities.	Eugene C. Sullivan.
25. Measurement of Illumination: A Defense for Human Eyes.	Dr. Clayton H. Sharp, Technical Director, Electrical Testing Laboratories.

Number and Title	*Contributor or Source of Information*
26. Outwitting the Marine Borers: Mighty Destroyers of Wooden Marine Structures.	Prof. C. A. Kofoid, University of California, member of San Francisco Bay Marine Piling Committee.
27. Tight Flexible Joints for Submarine Pipes: A Water Supply Problem.	Alfred D. Flinn, formerly Deputy Chief Engineer, Catskill Aqueduct.
28. A Serbian Herdsman's Contribution to Telephony: An Example of the Inborn Spirit of Research.	Dr. M. I. Pupin.
29. An Early Rotary Electrical Converter: The Solution of a Welding Problem.	Dr. Hermann Lemp.
30. What Matter is Made of: A Modern Conception.	Dr. W. R. Whitney.
31. Teredos and Tunnels: One of Nature's Engineering Suggestions.	B. H. M. Hewett, of Jacobs & Davies, Consulting Engineers, New York, N. Y.
32. A Farmer's Phenological Records: A Tale of Remarkable Individual Research with a Sad Sequel of Loss Due to Isolation.	Robert E. Horton, Consulting Hydraulic Engineer, Voorheesville, N. Y.
33. The Naval Tortoise Shell: Development of the Defensive Element of Warships.	Dr. Hermann Lemp.
34. Compressed Air for Underwater Construction: A Means for Making Practicable Many Difficult Foundations and Tunnels.	B. H. M. Hewett.
35. The Discovery of Manganese Steel: Its Metallurgical Paradoxes.	Henry D. Hibbard, Consulting Engineer, Plainfield, N. J.
36. A Story of Velox: Overcoming Difficulties by Research and Perseverance.	Dr. Leo H. Baekeland.
37. Pattern-Shop Research: Early Development of Hydraulic Turbines.	Robert E. Horton.
38. Smelting Titaniferous Iron Ore: Prospector and Researcher.	W. M. Goodwin, Editor, Canadian Mining Journal, Gardenvale, P. Q.
39. The Birth of Bakelite; Its Growth: An Adventure with Synthetic Resins.	Dr. Leo H. Baekeland.
40. Palladium: Danger in Discrediting the Unlikely.	G. Gore, in "The Art of Scientific Discovery."
41. Alchemistic Symbols.	Brochure by James Lewis Howe, Washington and Lee University, written for Baker & Co., Inc.
42. Temperatures of Stars.	Dr. W. W. Coblentz, Physicist, Bureau of Standards, Washington, D. C.
43. Kinematic Models of Electrical Machinery: Reducing a Phenomenon to a System of Simultaneous Equations.	Vladimir Karapetoff, Professor of Electrical Engineering, Cornell University, Ithaca, New York.

Number and Title	*Contributor or Source of Information*
44. Measuring Molecules: A Research in Pure Science Often Has Many and Unexpected Practical Applications.	Dr. Irving Langmuir, General Electric Research Laboratory, Schenectady, N. Y.
45. Titanium Products and Their Development.	Andrew Thompson, General Manager, The Titanium Alloy Manufacturing Company, Niagara Falls, New York.
46. Brighter Than the Sun: Light of Wires Exploded by Electrical Discharges.	Dr. J. A. Anderson, of the Mt. Wilson Observatory, Passadena, California.
47. Decomposing the Elements.	Dr. Gerald L. Wendt, Kent Chemical Laboratory, University of Chicago.
48. Malleable Iron: Its Great Improvement by Cooperative Research.	Enrique Touceda, Consulting Engineer, Albany, N. Y.
49. The Upper Critical Score: First Measurement of the Higher as Well as the Lower Limits of Intelligence, Beyond Which It Is Not Profitable to Employ Applicants for a Particular Type of Job.	Dr. W. V. Bingham, Director of Cooperative Research, Carnegie Institute of Technology, and member, Personnel Research Federation.
50. Wood and Moisture.	Forest Products Laboratory, Madison, Wisconsin, Carlile P. Winslow, Director.
51. The Hydrophone or Hydropelorus.	Dr. H. C. Hayes, Physicist and Sound Aide, U. S. Navy.
52. Marine Sounding by Sound: The Sonic Depth Finder.	Dr. H. C. Hayes.
53. A New Method of Measuring the Flow of Water.	Norman R. Gibson, Hydraulic Engineer, The Niagara Falls Power Co., Niagara Falls, New York.
54. A New Radio Antenna.	James Ashton Greig, B. S. E. E., Associate Editor, "Electric Traction"; formerly radio engineer, Marconi Wireless Telegraph Company of America and 1st Lieutenant, Radio Co. A., 331 F. A. 89 Inf. Div., U. S. A.
55. Conversion of Electromagnetic Energy into Useful Heat.	E. F. Northrup, Vice-President and Technical Adviser, the Ajax Electrothermic Corporation, Trenton, New Jersey.

APPENDIX A

GRAPHITIC CORROSION OF CAST IRON

By J. Vipond Davies, Member, Am. Soc. C. E., A. I. M. E. and Engineering Foundation; President, United Engineering Society.

HISTORICAL REVIEW

THE PAST THREE DECADES have covered the period of introduction of electric traction within the boundaries of cities and built-up communities. That period corresponds with the injury to, and depreciation of, underground structures, classed comprehensively in the general category of electrolysis. Better knowledge and improvement in electrical and mechanical design and construction have greatly reduced the effects of electrolysis arising directly from leakage of electric currents, but there are many cases where effects resembling those of electrolysis may be occasioned and may produce serious depreciation of submerged structures, which are not produced by what are ordinarily recognized as electric currents, but by other causes. Such conditions originated an investigation, hereinafter described, of a case involving graphitic corrosion of cast iron, which in its character and effect does not appear to resemble very closely the corrosion of any other of the ferrous metals and affects practically only what is ordinarily known as gray cast iron, or in other words, metal having the constituent carbon largely in a graphitic form.

The history of this form of corrosion is not new, as in the year 1840 a paper read by Robert Mallet before the Institution of Civil Engineers (Proc. Inst. C. E., Vol. I), describes the graphitization and seeming metamorphosis of cast iron after continued immersion in sea water. So little has been done in this particular study that even the most recent authorities revert to the findings of Mallet.

So little is it further considered to be of importance that in 1922 a communication from the U. S. Bureau of Standards read as follows:

> "I have your letter of November 11 in regard to the matter of so-called 'graphitic corrosion of cast iron.' During the past year or so I have noted a number of references to what has been described as 'graphitic corrosion of cast iron' and these

> references have been of such character as to imply that what is called 'graphitic corrosion' is corrosion of a distinct type, differing in some way or other from ordinary corrosion. I desire to call your attention to the fact that what is now being referred to as 'graphitic corrosion,' is simply corrosion of gray cast iron under such conditions that the graphite in the iron and the black oxide, which is quite frequently formed as an end product of corrosion, remain in place at the surface of the iron. Practically all cases of very rapid corrosion of gray cast iron buried in soils are cases which answer the description of the so-called 'graphitic corrosion.'
>
> "Gray cast iron contains several per cent by weight of carbon in the form of graphite and because of the low density of the graphite as compared with iron, the volume occupied by the graphite is relatively large. When iron corrodes in the presence of a limited supply of oxygen, as is generally the case with buried pipes, the end products, instead of being red oxide, are black oxide of iron, which is precipitated within the structure of residual graphite, thus giving it mechanical support and causing it to retain its original form. Analyses made of the material deposited in large pits in cast iron pipes generally show that it consists of an admixture of graphite and black oxide of iron. We have examined hundreds of cases of corrosion due to stray railway currents and in general it has been found that where the corrosion is very rapid and more particularly where the pipes are laid in rather heavy soil, there is deposited in the pits this admixture of graphite and black oxide of iron, which retains the form of the original iron. On casual inspection it may appear that the pipe is in good condition, but on more careful examination with a pointed hammer or knife, it will be found that the structure is fragile and in many cases easily cut away with a knife.
>
> "The point I would like to emphasize is that the so-called 'graphitic corrosion' is not a newly observed phenomenon nor is it in any material sense different from any case of subsurface corrosion of gray cast iron. It does not appear to be desirable, therefore, to regard this as something that calls for a separate investigation as a special problem."

This latter conclusion is apparently drawn in disregard of the seemingly totally different physical characteristics of this species of corrosion from those of any other metal or alloy as well as of the enormous value of and damage to, engineering structures of cast iron existing in soils saturated with water, which oftentimes may be highly injurious to such material of construction. The increased use of this material makes it vitally important to study this species of corrosion and means of prevention, in advance of the final determination of the general subject of corrosion of other ferrous metals.

THE CASE IN HAND

ABOUT TWELVE YEARS ago, my attention was drawn to the case of certain structures in which, apparently, electrolytic damage was proceeding; the investigation has continued up to the present time. Exhaustive electrical surveys seemed to prove conclusively that stray currents were not involved in the case. At that time it was not known that the waters in the soil were in any way likely to be injurious. The first step was to investigate completely the chemical character of the waters in the soil and trace their origin and extent. This disclosed the injurious character of those waters.

The next step, which extended over several years, was to introduce into the soil adjacent to the structures prepared test samples of metal similar in composition to that of the structures themselves and to demonstrate experimentally whether stray currents were responsible for electrolytic corrosion. These test samples were prepared in pairs, one sample being metallically attached to the structure and the other sample of each pair being carefully insulated from the structure. All these samples were machined all over so as to have clean metallic surfaces exposed. After exposure for periods from one to five years, the results indicated that insulation or lack of it does not affect in any way the rapidity or extent of the corrosion and that the action has no relation to electrolysis by outside currents, but is due to action within the mass of the material itself, or, in other words, to direct electro-chemical process. Some samples were completely graphitized within one year, others in close proximity were little affected in the longer periods.

The metallographic examination in this investigation has been made by Professor William Campbell, Ph. D., Sc. D., of the School of Mines, Columbia University, New York, whose microphotographical work has been done with the greatest skill and has been of great value in reaching an understanding of the structure of gray cast iron in its original and in its corroded condition. The study of the chemical problems involved has been by Ralph T. Goodwin, Ph. D., formerly of Columbia University.

Other Studies

As several other scientific bodies, both here and abroad, are engaged, and have been engaged for several years, in compiling complete bibliographies of the corrosion of iron and steel in connection with studies of this subject, it seems that no useful purpose can be served by attaching to this report any incomplete bibliography.

It seems worth mentioning, however, that the Iron and Steel Institute, of 28 Victoria Street, London, SW (New York, Spon and Chamberlain) published in 1922, as one of the Carnegie Scholarship Memoirs, a book called "The Corrosion of Iron," by J. Newton Friend, D. Sc., Ph. D., F. I. C., which gathers together in a compact form a great mass of recent research on this subject, quoting therein a large number of published writings. The colloidal theory of corrosion is treated in this book and the conclusion is reached that this theory offers satisfactory explanations for many phenomena which cannot be explained by any other theories, and that it suggests new lines of attacking the problem of the protection of iron and steel from oxidation.

Still more recent is the Sixth Report of the Corrosion Committee of the Institute of Metals (36 Victoria Street, London, SW) just published. A summary of this report states that the electro-chemical theory of corrosion gives a satisfactory account of the facts only under certain conditions and that, for a full explanation of all the baffling phenomena exhibited, recognition must be given to the important part in corrosion played by colloids. The Institution of Civil Engineers in conjunction with the Department of Scientific and Industrial Research of Great Britain has put in hand a research covering fourteen types of ferrous materials. Over one thousand specimens are being sent to the test stations all over the world to be exposed to the action of sea water. Sir Robert Hadfield, of Sheffield, has stated that the present annual wastage in iron and steel alone amounts to nearly three and a half billion dollars. Knowledge of the means whereby this may be reduced or prevented is evidently worth getting.

Results and Remedies

With the above in mind, the following statement represents briefly the main results of the studies made recently on the particular problem presented.

1. Graphitic corrosion is probably an electro-chemical reaction set up within the substance.

2. This reaction is caused by a large number of minute voltaic cells working in an electrolyte, usually a weak acid although neutral or alkaline solutions may in certain cases act as an electrolyte.

3. The electrodes, in the case of gray cast iron, are flakes of graphite and iron in contact.

4. The corrosion is not limited entirely to the iron content; as the other components of the alloy also disintegrate.

5. Contact with metals lower in the electro-motive series hastens the corrosive action.

6. Stray electric currents hasten the reaction.

7. Corrosion starts at the cathodic graphitic flakes and spreads out from them.

8. The white iron areas, or cementite, or phosphide-eutectic patches are attacked last of all and act as a support for the graphite and for the iron oxide formed.

9. Under identical conditions, gray cast iron is more corroded than dead white iron, as the latter has less graphite. As a matter of fact, containers of white cast iron are frequently used for storage of acids with satisfactory results.

10. Cast irons high in silicon are non-corrosive. Any graphite present occurs as tiny isolated plates. This kind of iron is brittle, cannot be machined, is difficult to melt for casting and is not used in engineering structures.

11. The protective measures consist of keeping the electrolyte from the surface and of neutralizing the acid or alkaline reaction of the liquid surrounding the surface.

As corollaries from these main results the following are noted:

(a) Variation in the results dependent on variation in the chemical composition of the electrolyte.

(b) Variation in the results dependent on variation in the chemical composition of the alloy.

(c) Variation in the results dependent on the structure of the alloy, i. e., in the size, shape and grouping of the graphite flakes and other constituents.

(d) Gray cast iron which has had its silicious skin removed by machining is much more subject to attack than that which retains its skin intact.

(e) Variation in the results dependent on variation in external influences: e. g., presence or absence of stray electric currents, temperature, renewal of electrolyte, and the infinite variations possible in the surrounding material.

In general, the less homogeneous the structure of the cast iron, the greater the graphitic corrosion. This is, doubtless, because the electrolyte solution is more free to enter the metal as well as because such metal provides the anode and cathode metals necessary for the existence of the voltaic cells which are the cause, or one cause, of this form of corrosion.

In pure waters, corrosion and depreciation of gray cast iron are extremely slow and minute, in fact may be considered as quite negligible; while in any water which will act as an electrolyte, the process of graphitic corrosion may be anticipated.

In injurious waters, or soils containing such waters, gray cast iron will be acted upon by an electro-chemical internal process, unless the metal is protected against such action. A clear metal surface permits this action, even in very dilute solutions; whereas, even in highly concentrated solutions, the action is prevented or becomes quite negligible, if castings are made in moulds having burnt sand as a facing and if the castings are further protected by dipping in hot pitch or asphaltum.

From evidence at hand it would appear probable that the corrosion of gray cast iron in an electrolyte is accelerated in cases where the original construction was carried out under air pressure; so that large volumes of air were forced through the surrounding soil and waters (constituting an electrolyte), thereby fully saturating the solution with dissolved oxygen.

One thing is obvious from this study, that no underground engineering structure should be built without first determining as exhaustively as possible the chemical composition and reaction of the waters and soil in which such structures may be embedded.

Questions Unanswered

Since this investigation has reached conclusions which satisfied the immediate, practical needs, no further work is contemplated. This does not mean, however, that a wide field for further research does not exist.

There are many lines of inquiry still open and these should be followed, in the interest of science, whenever possible, by whomsoever may be qualified to conduct such research.

Among the questions which seem still to await answers, is an explanation of the heat which is generated by the corroded iron as it is removed from the electrolyte. A quite intense heat is produced by a further and rapid oxidization and the sample thereafter hardens.

Professor Campbell advances the theory that the procedure of graphitic corrosion of cast iron in an electrolyte proceeds inwards from the exterior exposed surface into the mass in a progressive way, or in other words, that the oxidization of the iron is less complete as the depth increases and that several different oxides exist. This probably is the explanation for the unquestioned fact that a corroded sample removed from the electrolyte and dried when carved with a knife, generates heat so rapidly as actually to char and ignite a sheet of paper on which the particles are placed. In this case apparently the progressive stages of oxidization of the mass become complete on exposure to the air and so, after complete oxidization, the mass itself or the particles themselves harden in the form of the completely oxidized material.

The chemists and physicists who have studied this question of graphitic corrosion, do not satisfactorily explain, up to the present time, the further unquestioned fact, that metal which has suffered complete metamorphosis by what we have called graphitic corrosion, remains of constant volume, exhibits in the corroded condition even the original tool marks, notwithstanding the more or less complete condition of oxidization of the corroded metal, the resulting material, both in appearance and form, seeming to be identical with the original metallic structure. The various authorities seem to differ in their theories on this point, and, if for no other reason, this one phenomenon constitutes a distinct difference between this form of corrosion and any other with which engineers are concerned.

During the last few years, several scientific societies and individuals have undertaken research work along these lines, whereas a few years ago the field had scarcely been scratched. National Research Council, Washington, D. C., has a Committee on Corrosion, which is collecting information on this subject in its broadest interpretation and serving as a clearing house. Under these circumstances, I am of the opinion that the funds of Engineering Foundation should not be devoted to further research along these lines.

Appendix B

INTERNAL STRESSES IN METALS[1]

By E. P. Polushkin, formerly Chief Inspector in the United States, of the Russian Artillery Commission, and of the Russian Mission of Ways of Communication.

STUDIES CONDUCTED AT SCHOOL OF MINES, COLUMBIA UNIVERSITY, NEW YORK.

Note: I have kept in close touch with Mr. Polushkin's work and believe that he has obtained some interesting results, proving undoubtedly that the vibrations on the surface of a metal are influenced by the grain structure of the metal itself. The experiments which have been made, however, indicate that the differences in vibrations are so very slight that the practical application of this idea would be extremely difficult.

Arthur L. Walker, Member of Engineering Foundation, Professor of Metallurgy, School of Mines, Columbia University.

First Study, Reported May, 1922

EFFECT OF INTERNAL STRESSES ON NODAL LINES

Experiments with Steel Plates

The investigation had as a purpose to find out first, whether any difference exists in propagation of mechanical vibrations in metals when they are stressed and when free from internal stresses, and, second, whether it is possible to apply vibration as a practical means for detection and measurement of internal stresses in metal. This broad problem requires much time, continued efforts and a variety of facilities, but the time and the facilities available to me were so limited that I was able to do only a very small part of the proposed work. I had to spend much time in constructing the apparatus necessary for the proper observation of nodal lines in vibrating plates, also, in preparing the plates; so these experiments may be called only preliminary.

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[1] These progress reports are published especially for the information of others who may be working in this field, or contemplating such work.

The simple method for disclosing the lines of no motion, or *nodal lines*, called also *Chladni figures,* in a particular case when the plate is fixed in the center and has free edges, consists in scattering fine powder over the surface of the plate and drawing a violin bow across one of its edges while any other edge may be damped by touching it with a finger-nail or otherwise; by the waves of vibration the powder is tossed away from certain parts of the surface and collects along nodal lines. They represent such places of the surface as receive simultaneously two opposite impulses, the one which has a tendency to raise the particles of the plate above its level and the other, to lower them; in result, if both impulses are equal, this part of the plate will remain at rest. The powder accumulated over these parts will form a certain pattern, or figure. Our first purpose was to show that internal stresses have a certain effect on these patterns.

PREPARATION OF SAMPLES

EIGHT SAMPLES taken from plates of four different kinds of steel were used. All plates were accurately shaped square, 75 mm. x 75 mm., and their surfaces were polished. Six first samples were taken from plates one-eighth inch thick, two others from a plate one-quarter inch thick. The exact thickness was measured after polishing; it is given in Table I.

TABLE I DESCRIPTION OF SAMPLES

Number of Sample	Kind of Steel	Thickness of Sample, inch	Treatment of Sample
1.	Very soft steel...........	0.116–0.119	Hot rolled
2.	Same plate..............	0.125–0.147	Hot rolled
3.	Soft steel................	0.121–0.125	Cold rolled and annealed
4.	Same steel..............	0.124	Cold rolled
5.	Spring steel C= 0.70%...	0.124–0.132	Hot rolled
6.	Same plate..............	0.060–0.065	Quenched. Was cracked and corrugated, and so could be used only after a great part of thickness was reduced by shaping.
7.	Soft steel..............	0.233–0.238	Cold rolled
8.	Same plate..............	0.237–0.243	Cold rolled, and partly quenched; its lower portion was cooled rapidly by immersion in cold water.

To introduce internal stresses in the plates, three different methods were applied:

1st. Cold rolling. The samples were taken from cold-rolled steel plates and were compared with annealed samples of the same steel.

2nd. Partial quenching. The plate was heated to dull red and then immersed partly in cold water so that uneven cooling introduced internal stress.

3rd. Actual stresses were introduced in the plate by pressure.

Apparatus and Methods of Experimenting

Vibration of plates was produced by regular impacts of a small steel point. An electro-magnet of an ordinary door bell was used for this purpose after the bell itself had been removed and the head of its striker cut off (Fig. 2). The sharp end of the striker could be placed over any point of the surface of a plate at a desirable hight. When the current was passing through the electro-magnet the striker produced light blows and put the plate in vibration. The energy of these blows could be varied by changing the distance of the striker from the surface of a plate.

In the first series of experiments the plate was supported in its center by a small pin which was fastened up in a cross-bar; the latter could be moved along a vertical rod attached to a heavy base (Fig. 1). The edge of plate was free. This arrangement cannot correspond, however, to exact conditions required in such experiments, as the exact area of contact between the plate and the pin could not be determined; it depends upon the smoothness of their surfaces, and in some cases they may touch only in a few points.

In the second series of experiments, four points of contact were applied. The plate was supported by four sharp screws fixed in the base at equal distance of 70 mm. from one to the other and touching the plate near the points of its corners. In this arrangement, the area of contact was reduced to four points.

Then it was found that a plate lying freely on four supports is liable to move with its whole mass in lateral and vertical directions. These movements due to the uneven pressure of the weight of the plate upon four points, were very small, but they interfered with the formation of nodal lines. It was decided to make a table provided not only with four supporting screws, but, also, with four upper screws so that the plate could be clamped firmly. The screws of each pair had their points in one vertical line. By means of the lower screws, the plate could be leveled strictly horizontal. The base of the table was supported by four large screws (Fig. 2). The experiments made with clamped plates compose Series III.

In further experiments (Series IV) the plate was screwed in a vice for the purpose of introducing into it actual stresses. At each jaw of the vice a special plate was fixed provided with two horizontal steel points, and the plate to be tested was installed between these four points (Fig. 3). By screwing the vice a pressure could be exerted in the plate.

Experiments with the apparatus shown in Fig. 2 indicated that in this arrangement the impacts of the striker were oblique to the surface of the plate and this must have a certain influence on the pattern of nodal lines. Then a new testing apparatus with a straight vertical impact was designed, and its model was built but lack of time did not permit construction of the apparatus as it requires precise machine work. In this design a small weight (Fig. 4) is permitted to fall freely onto the surface of the plate.

If it is desirable to increase the weight, then additional small rings may be fixed to its upper part. The weight has a projecting part (a) which is engaged by a projecting part of the belt, so the weight is carried up to a certain hight and then released; it falls inside of a guiding tube which serves to secure a straight vertical impact (Figs. 5, 6). The belt runs around two small guide pulleys fastened up above the plate in the same frame that holds the guiding tube (Fig. 6); their axles are in one vertical line parallel to the axis of the tube. If necessary, the axle of the upper pulley may be raised or lowered in the frame so as to increase or reduce the hight of the fall. By changing the weight and the hight the energy of the falling body may be considerably varied. On the other hand, the frequency of impacts may also be changed by connecting the belt with different driving pulleys; their axle is driven by a motor of 1/20 horsepower. The apparatus may be constructed in a large size so as to produce impacts strong enough for vibrating a large mass of metal.

In regard to the powders that may be used in these experiments, several substances were tried—lycopodium, carborundum, emery No. 70, ferro-manganese 200 mesh, copper 200 mesh, lead 350 mesh, nickel 200 mesh, litharge 200 mesh and some others. The best results were obtained with emery No. 70 and ferro-manganese 200 mesh, and they only were used in these experiments. Generally speaking, the powder for this purpose must be fine, heavy and hard. The particles of a coarse powder may be too large to occupy a very narrow area of nodal lines and, therefore, they would partly place themselves over vibrating parts of the surface and would not be at rest in any case. On the other hand, a very fine powder is liable to lump and besides it does not collect over the nodal lines but on the contrary, occupies the parts with the most energetic motion. This is due to the action of air currents. Such an effect was observed with lycopodium (Rayleigh. The Theory of Sound, VI, Chapt. X). A heavy substance must be preferred because its particles do not jump into the air, but slowly move towards the nearest nodal line. If a powder is soft, it sticks to the surface and its movements are hindered.

In every experiment, the plate was arranged in a strictly horizontal position by means of supporting screws.

Description of Nodal Lines

Nodal lines of every series of experiments will be described separately, but first it is necessary to say a few words on their common features. By force of vibration, powder gradually moves towards nodal lines and finally occupies them. If the amount of powder is large, then the lines will be heavy, and it is possible to get them as heavy as one desires. Due to their angular shape, the particles will be interlocked one with others and will compose one solid mass which will be too heavy to be shaken by a minute wave of vibration beneath. Therefore, for exact drawing it is necessary to apply a small amount of powder just sufficient to cover all nodal lines.

The experiments showed that a regular pattern of nodal lines formed on the surface by accumulated powder does not remain the same, but as vibration continues still further it gradually breaks in a chain of lines or spots of a simpler form or even passes into a shapeless pattern. This may be explained by some imperfect conditions of the experiments, namely, by a change in the current power and by imperfect steadiness of the plate. Nevertheless, for every set of conditions under which experiments may be carried on, there exists a definite pattern of nodal lines.

I Series. The plate was fixed in the center, its edges free. It was excited in the middle of an edge. Nodal lines form a drawing similar to that of Fig. 7.

The comparison of drawings on plates No. 3 (cold rolled and annealed) and No. 4 (cold rolled) did not reveal any difference.

II Series. Plate was supported by four screws and excited in the center. Disposition of nodal lines is shown on Figs. 8, 9, 10.

Comparison of the Figures 8 and 9 shows that

(a) the central part of Fig. 9 is more rounded, almost circular, while that of Fig. 8 approaches to a rhomb;

(b) the angular shape of each branch of the pattern is more pronounced in Fig. 8 than in Fig. 9

During experiment, the pattern of Fig. 8 is more readily and more clearly formed than that of Fig. 9. This difference must be attributed to the presence of internal stresses in the cold rolled Plate 4. Plate 5 gives a less complicated pattern. When plates were excited at the middle of one edge they gave a pattern similar to Fig. 7.

Figs. 11 and 12 represent nodal lines on Plates 7 and 8 (¼ inch). The parts of the Fig. 11 have more rounded outlines, while on Fig. 12 the outlines are more angular. Plate 8 (Fig. 12) has a tendency to form a double line in the center. The pattern on the Plate 8 is formed in a more exact way. The difference must be ascribed to the internal stresses introduced in Plate 8 by quick and uneven cooling.

III Series. Plate was clamped at corners with four pairs of screws and excited in the center. Plates 4 and 3 were firmly clamped with upper screws. Dark line on No. 3 belongs to the plate but not to the pattern. Comparing Figs. 13 and 14 we find that cold rolled steel has a more perfect pattern and its double lines are wider than that of the steel after annealing. Plate 5 was clamped slightly.

It was noticed that when the Plate 4 was clamped slightly its pattern was different, the double lines became wider and the circumference in the center was not well marked (compare Figs. 16 and 13).

These experiments were repeated; always when Plates 4 and 3 were clamped firmly, their patterns were similar to Fig. 13, and when slightly clamped, they gave a pattern like Fig. 16. Severe clamping introduced actual stresses in plates and this was the cause why nodal lines assumed different pattern.

Series IV. Plate 3 was clamped in a vise and excited in the center. Nodal lines had a pattern shown in Fig. 17.

It was observed that the greater the pressure applied to the sides of the plate, the more angular became the central area between the two 8-like figures; when the pressure was small, both figures were rounded. Dissimilarity in shape of these figures is due to the uneven pressure from the two sides.

These few experiments showed that actual internal stresses, as well as potential, have a certain influence on the patterns of nodal lines, but more precise experiments are necessary to show it clearly.

Other Methods for Disclosing Nodal Lines

Figures formed on the plate by accumulation of powder do not mark the nodal lines exactly, and, therefore, some other methods should be applied if it is desirable to obtain precise patterns. Could it be possible to discover the nodal lines by deposition of a solid substance from solutions, or by etching the plate under vibration? It is known that a deposit of copper on a polished surface of a steel piece from solutions of $Cu\ Cl_2\ 2NH_4Cl$ in water adheres to the surface more strongly if the surface is smoother. Nodal lines may be considered as smooth parts of the undulated surface and for this reason they could be expected to hold the deposit firmly, while from other parts the deposit could be easily removed. With this thought, experiments were made, using different solutions of this salt. The center of the plate where impacts were to be applied was surrounded by a minute rampart of a plastic material, and the whole surface, excepting this small central area, was covered with a thin layer of a solution brought on the surface only after the plate began to vibrate. In this manner, the striker did not communicate any direct motion to the solution. These experiments did not reveal any nodal lines.

Similar experiments with etching reagents (picric acid in alcohol, nitric acid 5 per cent in alcohol) applied to the plate during its vibration, did not show any difference in etching of the quiet parts of the surface and that of the vibrated.

CONCLUSION

THE PRELIMINARY EXPERIMENTS showed that nodal lines may give some indications of the presence of internal stress in steel plates. Further development of this method requires precise apparatus and systematic investigation. Steel plates must be tested under definite tension or compression to find out the exact manner in which actual stresses affect the nodal lines. Some other methods for disclosing nodal lines in a more precise way than does the existing method, should be sought. Plates with internal stresses already determined by some other method must be studied systematically by the vibration method. Not only the nodal lines, but the whole phenomenon of propagation of mechanical vibrations in stressed metal needs to be investigated by means of some optical apparatus or phonograph arranged for recording waves of vibration.

SECOND STUDY. REPORT OF DECEMBER, 1922

THE PURPOSE of the present investigation is: first, to find out whether any difference exists in propagation of mechanical vibrations in stressed metal in directions parallel to stresses and perpendicular to them; and, second, to determine whether this difference can be used as a basis for detection and measurement of internal stresses. A special instrument, Fig. 18, has been designed for indicating vibrations. Experiments were made on steel and brass plates stressed by cold work; vibrations were incited in them by the impact of a small falling body.

Plate S to be tested is supported by four sharp screws, and when carefully leveled, plate A of the instrument is lowered and fixed slightly above it in a strictly parallel position. Plate A is fastened up by means of a ball-and-socket joint to sleeve B, which can move up and down along post C, fixed in the base of the instrument.

Three openings are made in plate A, one, round, in the center, and two straight and narrow, at right-angles to each other. Arm D can be rotated around a bushing in the center of the plate and may be put over one or the other of the straight openings. This arm has a slot in which part L moves with a bearing of a small lever (needle) F. Hammer E may be raised to a desirable angle of the scale, and when it drops strikes plate S through the central opening. Vibrations of plate S are recorded by a fine glass needle F, one end of which lightly touches the surface of the plate, and the other has a small mirror M at the end. This needle is supported by a glass axle and glass tube bearing. It is almost balanced, and, due to its lightness and to the smoothness of glass surfaces, rises at even minute vibrations of plate S. The magnitude of vibration is determined as a function of the angle of inclination of the needle. The tangent of this angle is measured by means of scale R and telescope T.

Before experiment, a certain division (a) of the scale is brought to coincide with a line in the telescope; when the hammer drops, the wave of vibration, in plate S, raises the end of needle F and then new divisions of scale can be observed in the telescope. The difference between the extreme division observed and the first one (a) is taken as the tangent of the angle of inclination.

Having found the magnitude of vibration in one direction, e. g., in the direction of stressing, the arm D is placed over the second opening, at right-angles to its first position, and a similar record taken. If both observations were done under identical conditions, the difference between the two records should be charged to the presence of internal stresses in metal.

Since the bearing of needle F can be moved in the slot of arm D, the end of the needle may be placed at any desirable distance from the impact point.

We may say that by this method the resilience of the stressed metal is measured in two directions—that of stressing, and at right angles.

On experimenting with this instrument, it was found that it must be improved in parts in order to serve the purpose. It is desirable to replace the hammer by a glass or quartz tube with a hard, rounded end falling straight vertically on the plate to be tested. The second record of vibration should be made with the needle in the same position as in the first, and, therefore, the table with the sample must be rotated at right angles. Also, it may become necessary to record the magnitude of vibrations autographically instead of observing divisions of the scale in the telescope.

SECOND STUDY. REPORT OF FEBRUARY, 1923

THE FOLLOWING ALTERATIONS were made in the arrangement of the apparatus described in report of December, 1922. First, hammer E was replaced by a glass rod falling vertically. The lower end was carefully rounded so as to form a hemi-spherical surface and in the upper end a needle was sealed, to which a fine string was fastened. The rod (striker) may be raised to any hight; its strictly vertical movement was secured by means of guides A and B, Fig. 19. Both guides have four small glass tubes that can revolve around glass axles with very little friction; between them the striker is placed so that it touches the tubes only on four points at each guide. Due to this arrangement more regular impact is secured. The hight of rebound is increased and calculation of the energy of impact facilitated as compared with the rotating hammer described in the December report.

Second, the table supporting the plate to be tested was made to rotate around a vertical axis. Therefore, the plate may now be tested in any direction without changing the position of the recording needle. As described previously, this needle has a mirror at one end which reflects divisions of the scale placed at the telescope; the other end touches the surface of the plate. It would be difficult to change the position of the telescope and scale when a record at right angles has to be taken.

The scale is divided into 1/20-inch divisions and placed at the distance of 17.5 inches from the mirror. Divisions of the scale reflected by the mirror are clearly seen in the telescope. When the glass rod strikes the plate, the lower end of the recording needle is raised and the mirror is lowered. The tangent of the angle of inclination may be measured by the number of divisions passed by the cross-line in the telescope.

The following difficulties were met in experimenting: The observation in the telescope showed that the recording needle is very sensitive to any vibration inside or outside the room. To prevent interference of these vibrations with the correct reading it is necessary to install the apparatus on a solid base; it was on a table. Further, the image of the scale is moving, after impact, so rapidly as to make difficult the exact reading of the extreme division crossed by the horizontal line in the telescope. This difficulty may be overcome by autographic recording of the whole movement of the mirror on photographic paper. Further development of the apparatus is necessary.

The purpose for which the apparatus was constructed was recording the vertical component of vibration caused in the plate by the impact. Now it seems necessary to change its construction so as to make possible the recording of both vertical and horizontal components of the vibration. This change may involve radical changes in the method of experimenting.

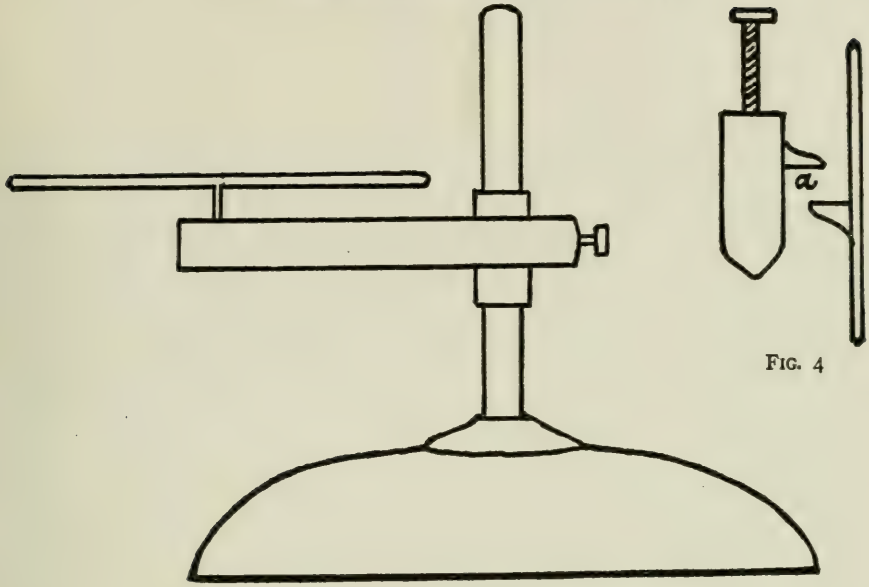


FIG. 4

FIG. 1

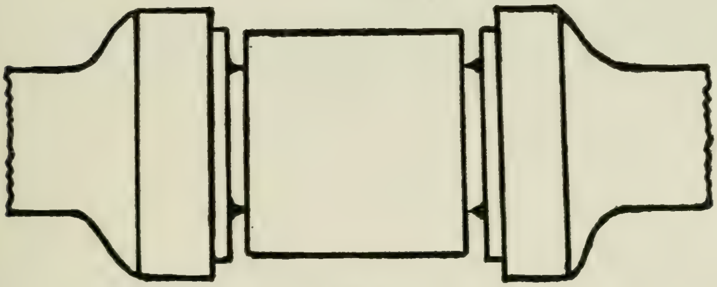


FIG. 3

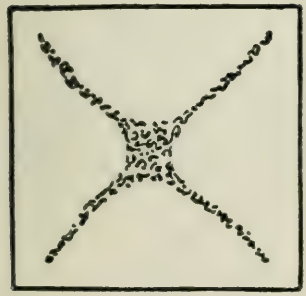


FIG. 7

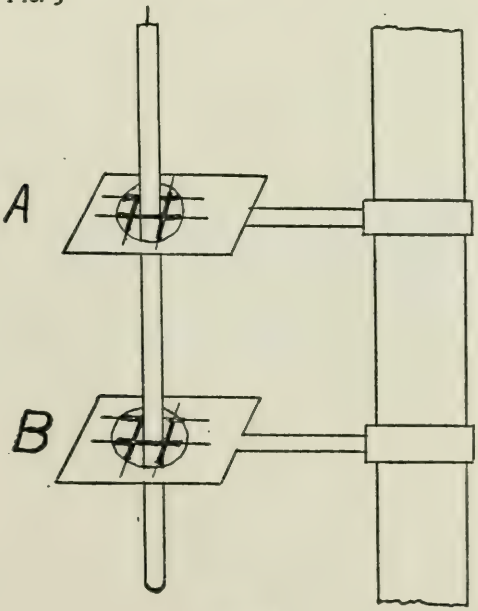


FIG. 19

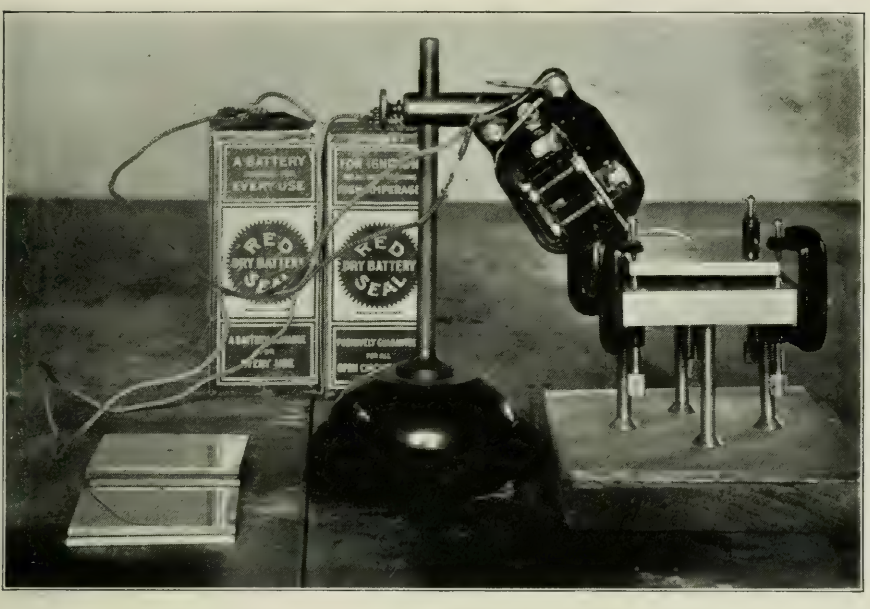
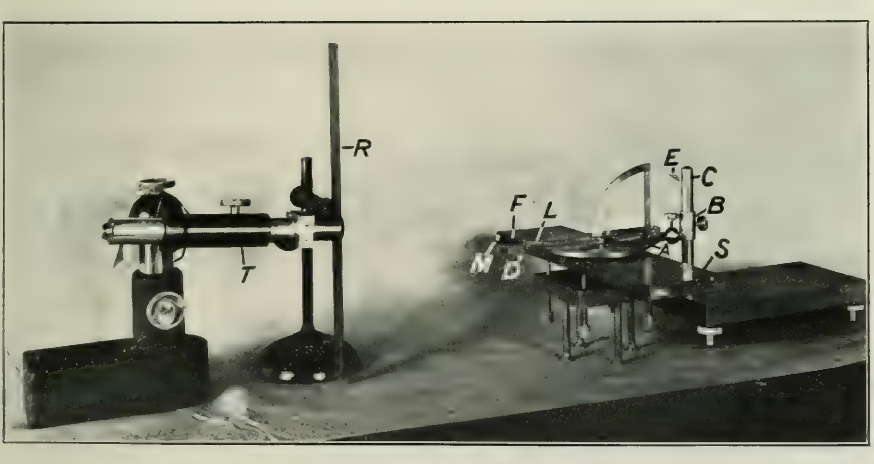

A BATTERY
EVERY USE
RED SEAL
DRY BATTERY
FOR IGNITION
HIGH AMPERAGE
RED SEAL
DRY BATTERY
OPEN CIRCUIT

Fig. 2


R
T
F
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N
D
E
C
B
A
S

Fig. 18

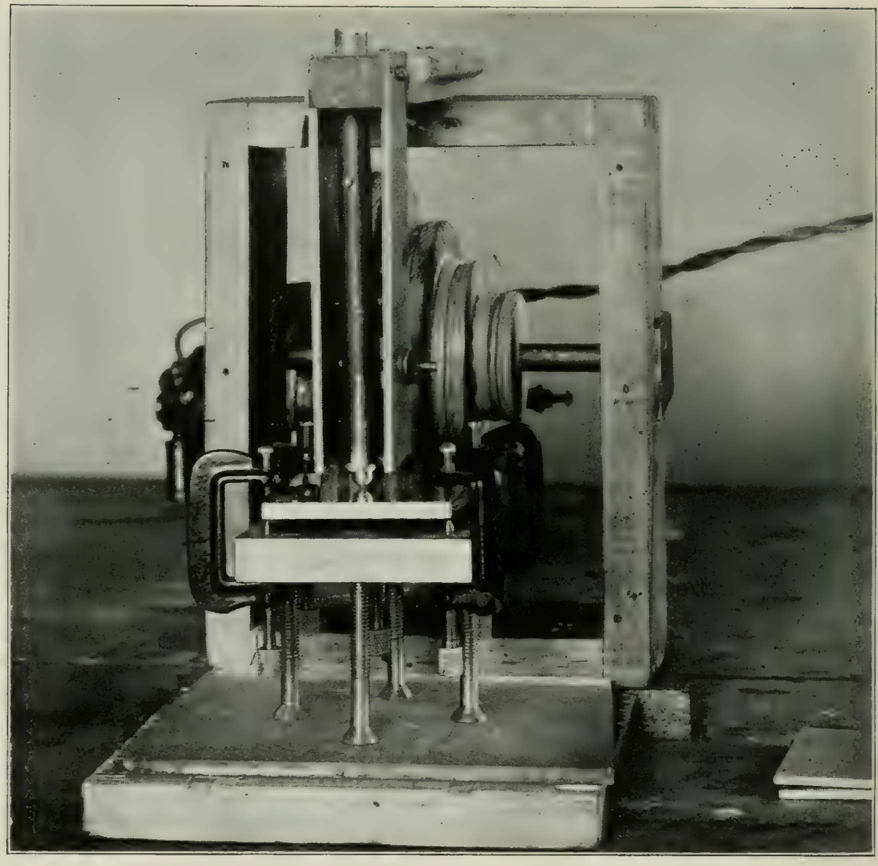

Fig. 5

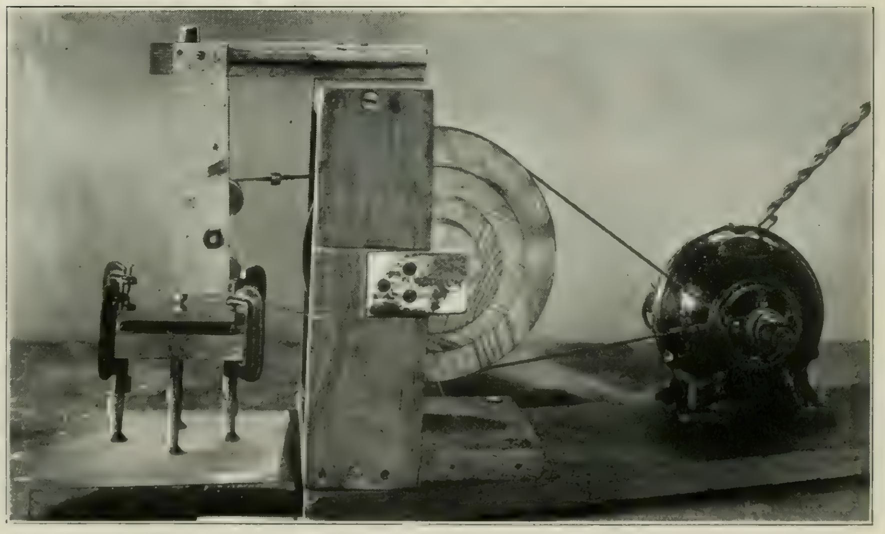

Fig. 6

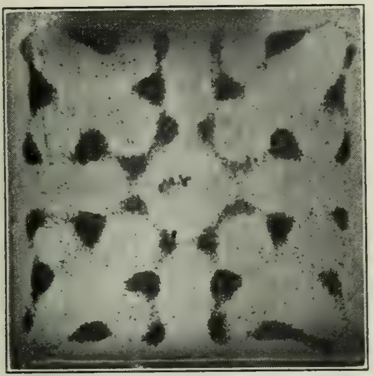

Fig. 8
Plate 4 (cold rolled)

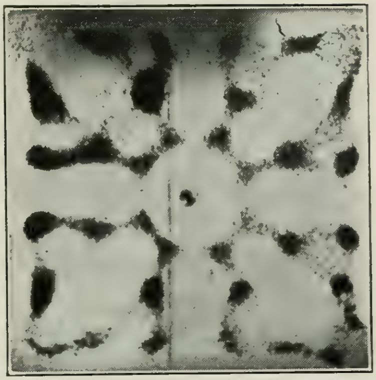

Fig. 9
Plate 3 (cold rolled and annealed)

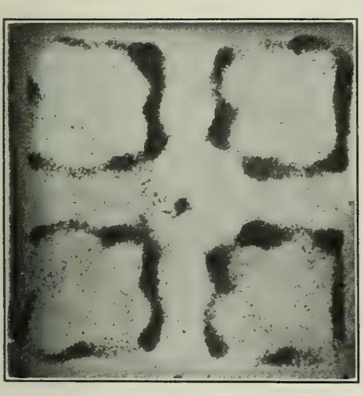

Fig. 10
Plate 5 (spring steel, hot rolled)

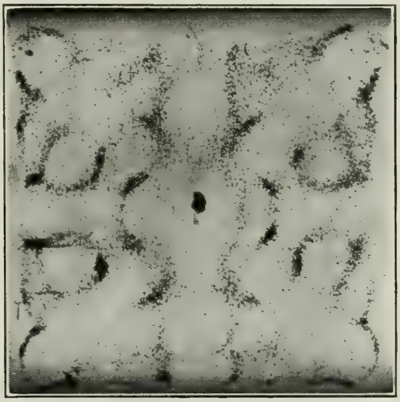

Fig. 11
Plate 7 (cold rolled)

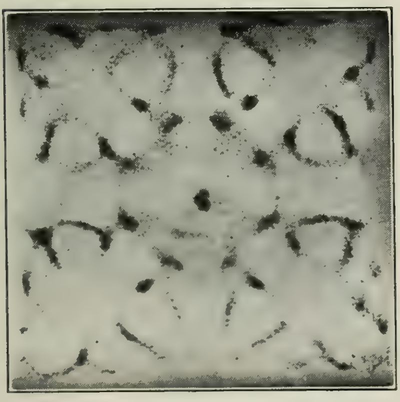

Fig. 12
Plate 8 (heated and one half quenched in cold water)

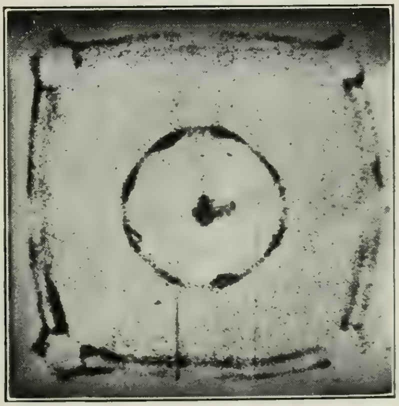

Fig. 13
Plate 4 (cold rolled)

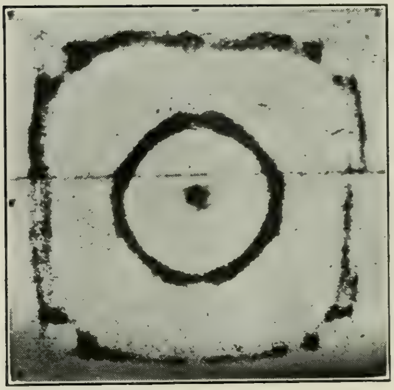

FIG. 14
PLATE 3 (COLD ROLLED AND ANNEALED)

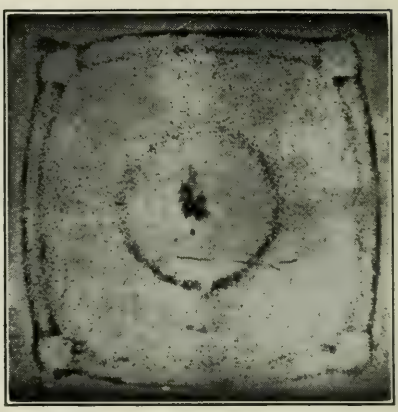

FIG. 15
PLATE 5 (HOT ROLLED)

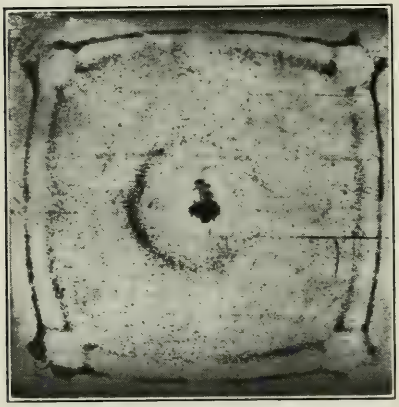

FIG. 16
PLATE 4. CLAMPED SLIGHTLY

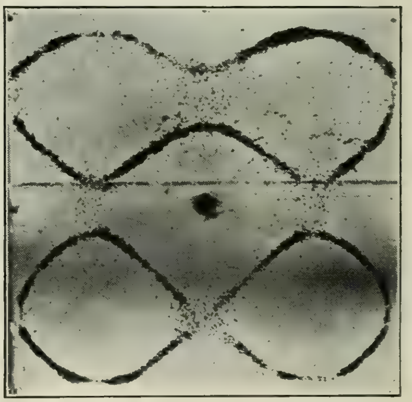

FIG. 17
PLATE 3. CLAMPED IN VISE

(The small black spot in the center does not belong to the patterns; it was left by the striking point.)

THE FATIGUE OF METALS

A RESEARCH AT
THE ENGINEERING EXPERIMENT STATION OF
THE UNIVERSITY OF ILLINOIS

By H. F. MOORE and T. M. JASPER

SECOND REPORT

ABRIDGED AND PARTIALLY RE-WRITTEN FROM
BULLETIN 136 OF THE
ENGINEERING EXPERIMENT STATION
OF THE UNIVERSITY OF ILLINOIS

1921–1922

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[1] Revised to May, 1923.

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RESEARCH IN FATIGUE OF METALS

Scope of Work

This report covers two nickel steels, a number of heat treatments of various steels, determination by various methods of endurance limits under reversed stress, special long-time reversed-stress tests, tests on specimens retested after having withstood ten million or more cycles of reversed stress near the original endurance limit, effect of speed of reversal of stress on the endurance limit, endurance tests of overstressed steel, and endurance limits for various combinations of tensile and reversed-bending stresses. Additional confirmation has been gotten of the existence of an endurance limit.

Introduction

Continuation during 1922 of the cooperative investigation begun in 1919 was financed largely by the General Electric Company. This company and others are collaborating with the University of Illinois, National Research Council and Engineering Foundation in extending the work through 1923, and succeeding years. The program will include ferrous metals at high temperatures, other ferrous metal problems and a study of non-ferrous metals, particularly, alloys of copper.

Publication No. 4 (1922) of Engineering Foundation (now out of print) and Bulletin No. 124 (1921) of the Engineering Experiment Station, University of Illinois, contain the first report on this investigation. They can be seen at many libraries. Bulletin 124 can be obtained from the Director of the Engineering Experiment Station.

Conclusions

The tests herein recorded have all been made on specimens of wrought ferrous metal, free from flaws and large inclusions, with continuous series of cycles of stress. Tests in reversed bending, combined reversed bending and steady tension, and reversed tension are included. All specimens were turned with the longitudinal axis in the direction of rolling of the steel. The information gained from these specimens may not be true for steel with serious flaws or large inclusions, nor should such conclusions be extended to cast steel, cast iron or non-ferrous metals. Subject to the above limitations, the conclusions may be summarized as follows:

(1) All available test data confirm the existence of an endurance limit for wrought ferrous metals, "endurance limit" being defined as the unit stress below which a metal is capable of withstanding an indefinitely large number of reversals of stress.

(2) All known test results confirm the conclusion that the endurance limit of a wrought ferrous metal may be determined with a fair degree of accuracy by a short-time test in which the rise of temperature under reversed stress is measured.*

---

* It is not certain that this conclusion holds true for wrought ferrous metals having a Brinell hardness higher than 400.

(3) The tests herein recorded confirm the conclusion previously drawn that for wrought ferrous metals the endurance limit seems to be correlated with the ultimate tensile strength, with the Brinell hardness number, and in a much smaller degree with the yield point and the proportional elastic limit. No correlation was found between the endurance limit and the ductility, the results of Charpy impact tests of notched bars, or repeated-impact tests.

(4) The effect of speed of reversal of stress on the determination of the endurance limit seems to be slight below a speed of five thousand revolutions per minute for tests made on a Farmer rotating-beam testing machine. A slight increase of endurance limit was noted for increased speed of reversal of stress.

(5) The results of the tests of specimens with various temperatures of "draw" after oil-quenching indicate that for the carbon-steel specimens tested neither the ultimate tensile strength, the endurance limit for flexure, nor the ductility was appreciably affected by draws at a temperature lower than 600 degrees Fahr. For the nickel-steel specimens for draws up to 400 degrees Fahr. the ultimate tensile strength and the endurance limit for flexure diminished slightly while the ductility increased a little. For draws at higher temperatures the changes in values of strength and ductility were more marked, the ultimate tensile strength and endurance limit decreasing, and the ductility increasing. Whatever advantages may be gained by draws below about 600 degrees Fahr. such as relief from internal stress and increased machine-ability, may be attained with but little, if any, sacrifice of tensile strength or of endurance strength under flexure.

(6) The results of tests of the specimens subjected to severe tensile overstress before being tested in reversed bending indicate that a few applications of stress, well above the proportional elastic limit of the metal, lowered the endurance limit under subsequent reversed stress, the endurance being diminished by 22.9 per cent of its original value for one set of specimens. The effect of polishing the specimens after overstressing has not yet been investigated. Placing the overstressed specimens in boiling water did not seem to have any appreciable beneficial effect on the endurance limit.

(7) From the test data recorded herein the following tentative formula is given for wrought ferrous metals as expressing the relation between the endurance limit for cycles of completely reversed stress and the endurance limit for cycles of stress not involving complete reversal:

$$S_r = S_{-1}\left(\frac{r+3}{2}\right)$$

in which r is the algebraic ratio of minimum stress to maximum stress during a cycle of stress (for completely reversed stress, $r = -1.0$), S_r is the endurance limit for ratio r, and S_{-1} the endurance limit for completely reversed stress.

(8) If a specimen or machine part is subjected to cycles of repeated-bending stress higher than the proportional elastic limit of the metal, the tests indicate that there may result a failure by excessive distortion of the specimen or the machine part. The limiting unit stress under repeated bending should, then, never be considered as higher than the proportional elastic limit of the metal.

Note:—An interesting paper on "Fatigue of Metals," by C. F. Jenkin, Professor of Engineering Science, Brasenose College, Oxford, England, was printed in "The Journal of the Royal Aeronautical Society," March, 1923, together with discussion by other investigators. It describes ingenious models for illustrating fatigue actions in metals as well as giving other interesting information and theories relating to steels, copper and nickel.—*Engineering Foundation.*

Endurance Limit for Wrought Ferrous Metals under Reversed Stress

Recent Test Data.—Since publication of the first report, many additional test data have been obtained for specimens subjected to reversed stress.[1] Table 1 gives the chemical analyses for all steels tested since the first report and Table 2 the heat treatments used. The tests of specimens in reversed flexure were made on the same machine as was used for the first report. No new kinds of steel have been tested, although a number of different heat treatments have been used. Fig. 2 shows a special tension test specimen for static tests which was used when it was desired to make tension tests on the halves of broken "Farmer" specimens. In addition to the repeated-stress tests recorded in this bulletin, static, hardness, impact, and repeated-impact tests were made on specimens of the metals. The apparatus and methods of testing were the same as those described in the first report.

Test Data from Other Laboratories.—An extensive series of repeated-stress tests of ferrous metals has been made by D. J. McAdam, Jr., at the U. S. Naval Engineering Experiment Station at Annapolis, Maryland.[2] The Annapolis tests covered a wide range of steels, and a number were run to 100 000 000 reversals of stress, and some even further. A rotating-beam type of testing machine with a tapered cantilever specimen was used.

An article by H. J. Gough of the British National Physical Laboratory[3] describes methods of making determinations of the endurance limit by means of rise-of-temperature tests and by means of deflection tests under reversed stress. Many test data were given with this article.

Rise-of-Temperature Test and Deflection Test under Reversed Stress.—Determination of the endurance limit by means of the rise-of-temperature test was made at the University of Illinois for each metal tested, and for each heat treatment, apparatus and methods being the same as those described in the first report. Table 6 gives values of the endurance limit as determined by the rise-of-temperature test and also by the test of specimens to destruction. Fig. 20 shows graphically the relation between the endurance limits determined by the two methods for all metals and all heat treatments studied to date.

Gough in the article previously mentioned showed that the cumulative effect of spreading fatigue failure was manifested not only by the rise of temperature in a reversed-stress specimen, but also by the undue increase of deflection as the magnitude of the stress was increased while cycles of reversed stress were applied to the specimen. Some preliminary studies of this deflection test have been made at the University of Illinois, but not enough work has been done to justify drawing any conclusions as to its value.

Summary of Evidence for Existence of an Endurance Limit for Wrought Ferrous Metals.—In the first report the endurance limit for a metal was defined as that unit stress below which the metal could withstand an indefinitely large number of reversals of stresses without failure; and the evidence for the existence of such a limit for the metals tested was given. The tests recorded herein tend to confirm the existence of an endurance limit, the evidence for which may be summed up under four heads:

---

[1] The results of repeated stress are plotted with values of unit stress as ordinates and with values of number of cycles of stress to cause failure as abscissae. Diagrams so plotted are called *S-N* diagrams. Like the *S-N* diagrams in the first report those given in Figs. 5 to 17 are plotted to logarithmic coördinates. In Fig. 19 the *S-N* diagrams are shown with Cartesian and with semi-logarithmic coördinates.

[2] "Endurance of Steel under Repeated Stress," by D. J. McAdam, Jr., Chemical and Metallurgical Engineering, Dec. 14, 1921, p. 1081.

[3] "Improved Methods of Fatigue Testing," by H. J. Gough, The Engineer (London), Aug. 12, 1921, p. 159, abstracted in "Mechanical Engineering" for October, 1921, p. 677.

(1) However they are plotted, *S-N* diagrams[4] for the reversed-stress tests carried out in the Investigation of the Fatigue of Metals all become either horizontal, or very nearly so, as the value of *N* is increased into millions. If the *S-N* diagrams become horizontal, and *stay so*, it means that, below the stress indicated by the horizontal part of the diagram, the specimen can withstand any imaginable number of cycles of stress. In the tests pertaining to this investigation the diagrams, so far as could be determined, became horizontal, and it does not seem unreasonable to assume that in any event they became so nearly horizontal that billions of cycles of stress would be required to cause failure for any unit stress materially below the value corresponding to the part of the *S-N* diagram which is horizontal, or nearly so.[5]

In connection with the existence of an endurance limit, the results of a few tests which extended beyond 100 000 000 reversals of stress are of interest. Three specimens which had run for 100 000 000 cycles of reversed stress at a unit stress just below the endurance limit were allowed to run on for a longer period with the same unit stress. Table 7 gives the results of these tests, showing that these specimens at least will withstand reversals of stress well toward a billion.

(2) In each *S-N* diagram there is a fairly well-defined "knee." This knee is best shown in *S-N* diagrams plotted to Cartesian coördinates (Fig. 19a gives *S-N* diagrams for several typical test series so plotted), but is also evident in *S-N* diagrams plotted to logarithmic coördinates and in diagrams plotted to semi-logarithmic coördinates (Fig. 19b shows semi-logarithmic *S-N* diagrams for the same tests as are plotted in Fig. 19a).[6] The knee in the *S-N* diagram seems to furnish evidence of some distinct change in the law of endurance at a stress corresponding very closely to the horizontal part of the *S-N* diagram, and still further to justify the view that the value of *S* at this knee—this value corresponds to that of *S* for the horizontal part of the *S-N* diagram also—is an endurance limit which is a criterion of the ability of the metal to resist repeated stress.

(3) Another short series of tests is also interesting in this connection. Some specimens which had run out to 100 000 000 cycles without fracture, under unit stresses just below the endurance limit, were retested under higher loads. As shown by Table 8, many of these specimens ran out to 50 000 000 cycles of stress (or more) with unit stresses *above* the endurance limit of the original material, the excess in one case (0.37 carbon steel) being 20 per cent. These tests give interesting indications of the possibility that under stresses near, but below, the endurance limit the resistance of material to reversed stress may be actually increased, perhaps by a re-adjustment of bearing between grains of the metal. This strengthening effect was especially noticeable for 0.37 carbon steel, 'normalized. This apparent increase of strength in steel stressed nearly to its endurance limit gives additional confidence

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[4] Note that this does not hold for diagrams in which one coördinate is some function of the reciprocal of *N*.

[5] In interpreting the results of the Annapolis tests, the experimenter judged that the *S-N* diagrams did not become horizontal, but had a slight slope downward. However, this slope was so slight that a reduction of unit stress of 15 per cent increased the value of *N* 1,000 times. Even for such machine parts as steam turbine shafts and discs the practical difference between considering the *S-N* diagram horizontal, and as having this slight slope is very small, as regards the effect on the determinations of allowable working stresses. In the plotting of the *S-N* diagrams for a series of reversed-stress tests it is felt that attention should be called to the fact that results for specimens which "ran out" unbroken to the chosen limit for values of *N* do not locate points *on* the *S-N* diagram, but rather points *on* or *below* the *S-N* diagram.

[6] This "knee" in the *S-N* diagram was not clearly apparent in the Annapolis tests. The test data for those tests were, for the most part, obtained for values of *S* not much above the horizontal part of the diagram, with few data above the region where the knee would probably be.

in the conclusion that, below the endurance limit, the ferrous metals will withstand an indefinitely large number of reversals of stress.[7]

(4) Another item of evidence in favor of the existence of an endurance limit is the marked rise of temperature which is noted under reversed stress if the value of S is above the endurance limit as determined from an S-N diagram. This is shown in Fig. 19c in which are plotted the results of rise-of-temperature tests on specimens of the same materials for which S-N diagrams are plotted in Fig. 19a and Fig. 19b. A glance at Fig. 19 will show that for the materials indicated an increased rate of rise of temperature is observed for stresses above the endurance limit. Fig. 20 shows a correlation curve for endurance limit determined by a rise-of-temperature test with the endurance limit obtained from an S-N diagram for all metals thus far tested in this investigation. The correlation is seen to be a very good degree of 1 to 1 correspondence.[8]

As far as could be ascertained in this study of metals, there is no experimental evidence which tends to discredit the existence of an endurance limit. Some writers have proposed formulae for repeated stress which would imply that such a limit did not exist, and that any stress, however low, will, if repeated often enough, fracture any material. These writers stated, nevertheless, that such formulae were given as *safe* ones to use rather than as formulae based on adequate test data, since there was no information available on tests extending to tens of millions of repetitions of stress.

It can hardly be asserted dogmatically that there exists for a ferrous metal an endurance limit below which the metal will stand any imaginable number of repetitions of stress; nevertheless in view of the four items of experimental evidence given in the preceding paragraphs, it is believed that there exists for a ferrous metal a limiting stress, which may be designated as the endurance or fatigue limit, and which even for the extreme case of parts of high speed machinery may be regarded as a limit of the strength of the material under repeated stress.

Whether for non-ferrous metals there exist endurance limits as well-defined as those for ferrous metals is a question not yet settled.

Correlation of Endurance Limit for Wrought Ferrous Metals with Other Physical Properties.—Recent tests give no reason to modify in any important respect the conclusions previously drawn: (1) that the endurance limit is not closely correlated with the results of impact tests or of repeated-impact tests; (2) that there is a decidedly uncertain correlation between the endurance and the elastic limits; (3) that for wrought ferrous metals there is a fair degree of correlation between endurance limit and ultimate strength, and between endurance limit and Brinell hardness; and (4) that there is a good degree of correlation between endurance limit of wrought ferrous metals determined from S-N diagrams and that determined by rise-of-temperature tests. (See Figs. 21 to 25 and 12.)

The following qualitative explanation of the correlation observed between the endurance limit and the ultimate tensile strength of a wrought ferrous metal is offered: When the metal is viewed through a microscope, the progress of the fatigue failure is seen to be a progressive fracture of small grains. The fracture may follow a path through grains, or less commonly, a path along grain boundaries; but it is a fracture which is observed rather than a distortion of grains such as seems characteristic of the state of the plastic flow. The plastic flow, as the stress is increased in a tension test, does not become appreciable below the elastic limit.

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[7] Recent tests reported orally by Dr. H. W. Gillett of the U. S. Bureau of Mines show similar results.

[8] Recent tests reported orally by Dr. H. W. Gillett of the U. S. Bureau of Mines indicate that this 1 to 1 correspondence may not hold for steels with a Brinell hardness number higher than 400.

The progressive fracture observed in a fatigue failure resembles a fracture in which lateral distortion (necking-down) is restrained, such a fracture as is seen in a tension test of a notched bar, or the threaded portion of a bolt. In an ordinary tension test the ultimate is reached before necking-down has developed to any great extent; and the tensile strength of a notched or grooved specimen is, in general, a function of the ultimate strength of the material as determined by a test of a standard specimen. In view of the fact that fatigue failure seems to be a progressive fracture with restraint of lateral deformation, it seems not unreasonable that the endurance limit of a material should be correlated with the ultimate tensile strength rather than with the elastic limit,[9] which is the characteristic of fatigue failure.

So far only sound metal has been tested; the correlation of ultimate tensile strength with endurance limit may not hold for metal with internal micro-flaws.

It has previously been noticed by various observers that there is a fair correlation between ultimate tensile strength and Brinell hardness.[10] It would seem reasonable, therefore, that if correlation exists between endurance limit and ultimate tensile strength, correlation between endurance limit and Brinell hardness will also exist up to the limits where the Brinell test itself begins to be unsatisfactory on account of the deformation of the steel ball. This occurs at a Brinell number about 400. This conclusion is borne out not only by the results of tests at Illinois but also by those of the Annapolis tests, and by the experience of experimenters at the British National Physical Laboratory. It is believed that the correlation between Brinell hardness, or ultimate tensile strength and endurance limit may be regarded as fairly well established for sound wrought ferrous metals up to a Brinell hardness number of approximately 400.

Significance of Endurance Limit.—The lack of correlation between the endurance limit and some other physical property of a metal does not signify that the latter is of no value as an index of the qualities of the metal. For example, there seems to be no correlation between the endurance limit of a metal and its ductility, yet the ductility of a material must be considered by the user. This lack of correlation simply indicates that under repetitions of a definite stress, ductility does not markedly affect the strength of a material, and that if there were any certainty that a machine part would never be subjected to extraordinary stresses, the ductility of the material would not need to be taken into account. This is the case for springs provided with stops to guard against excessive deflection; and oil-quenched high-carbon steel, a material low in ductility, is frequently used for those springs. Notwithstanding, for most machine parts there is a probability that occasionally they will be subjected to rather severe overstress. The parts of the running gear of a motor car furnish an excellent illustration of this point. For the material in such parts ductility is important in furnishing insurance against a disastrous, shattering failure under overstress. If a material is ductile, some hundreds of overstresses can be endured with no worse result than a slight distortion of the member. Moreover, it may be possible by means of straightening, heat treating, and polishing of parts to repair this rather severe damage. This illustration has been given at some length, because there is a tendency for engineers to use one test, and one test only, for judging a material and to feel that the adoption of one test implies the discarding of others. With our present knowledge, no single test can give an index of the usefulness of a material for all classes of service. The materials engineer should beware of regarding any single property of a metal—elastic limit, tensile strength, endurance limit, hardness, ductility, notched-bar value, etc.—as a complete indication of the usefulness of the steel. Static strength, resistance to impact, ductility under overstress, and resistance to repeated working loads are all important.

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[9] The picture here given of fatigue fracture is that of a minute crack starting at the very outset of the service of a machine part. This crack spreads very slowly at first, but very rapidly during the last few cycles of stress before final failure. Some elasticians picture the early stages of fatigue failure as a series of minute displacements of particles, each displacement involving inelastic action; actual rupture they consider as a late development in the history of a fatigue failure.

[10] Abbott, "The Relation between Maximum Strength and Brinell Hardness, etc." Proc. of A. S. T. M. Vol. XV, Part II, p. 42, (1915).

Miscellaneous Tests and Test Results

Tests under Reversed Shearing Stress.—In the first report some test results of specimens under reversed shearing were given. The shearing stress was set up by means of torsion; and the machine used was an Olsen-Foster reversed-torsion machine. Further tests with this machine have been made; the results are shown in Table 6 and in Figs. 16 and 18.

A reversed-torsion testing machine of somewhat different type from the Olsen-Foster has been designed. This machine (Fig. 3) has the specimen *S* attached at one end to the rotating head *H*, and at the other end to a rotating flexible beam *B*. At the end of this beam a load *P* is applied by means of weights or a spring balance through the ball bearing *R*. When the axis of the specimen is horizontal and the specimen is on the left-hand side of the shaft (as seen in Fig. 3), the twisting moment on the specimen is counter-clockwise; when the shaft of the machine has rotated 180 degrees and the specimen is on the right hand side, the twisting moment is clockwise; there is a complete reversal of torsional (shearing) stress during a rotation. When the length of the flexible beam *B*, the weight *P* at the end of the beam, and the moment set up in the specimen by the weight of the beam are known, the torsional moment and the shearing-unit stress in the specimen can be computed. The beam *B* is made flexible, especially in one direction, to minimize vibration, a dash-pot below R being also of service in this regard. This machine is operated at a speed of one thousand revolutions per minute. The specimen used in this machine is shown in Fig. 4. The results of tests are given in Table 6 and Fig. 17.

Results of reversed-torsion tests made with the Olsen-Foster machine check fairly closely those of the tests on the Illinois machine, and the ratio of endurance limit under reversed shearing stress to endurance limit under reversed flexural stress averages about 0.56, which is in fair agreement with the preliminary results as given in the first report.

Effect of Speed of Stress Reversal.—The effect of the speed of stress reversal on the results of repeated-stress tests is of consequence. In the first report results of seven series of experiments made in various laboratories were quoted to show that below about two thousand revolutions per minute the effect of speed of reversal of stress on the fatigue strength of steel specimens is small. Additional study of this problem has been made on five materials, steels Nos. 1, 5, 7, 9, and 10. Tests were made on Farmer rotating-beam machines at speeds of two hundred, fifteen hundred, and five thousand revolutions per minute. The results are shown in Table 9.

These results indicate that at a speed of two hundred revolutions per minute the endurance limit averages about two per cent lower than at a speed of fifteen hundred revolutions per minute, and that for a speed of five thousand revolutions per minute it averages practically no higher than at fifteen hundred revolutions per minute. These variations are not large; and while for any given comparison of materials it would seem wise to make tests at the same speed throughout, the effect of speed of reversal of stress on small specimens and machine parts does not seem to be very great.

The slight effect of speed on the results of fatigue tests made in the rotating-beam machine is an item of evidence that the abnormal stresses due to vibration and its resulting inertia effects are not large for this type of machine.

For machine parts in which a wave of stress is obliged to traverse a path of considerable length, as for example, a long rock drill, the interference between a wave of stress and the reflection from a previous wave may set up nodes of stress. In such cases the maximum stress may be very different both in location and in magnitude from the value computed by the ordinary formulae of mechanics of materials, which are developed from considerations of static equilibrium.

Results of Tests of Steel with Various Temperatures of Draw after Quenching.—Figs. 26 to 29, inclusive, show graphically the results of tests of steel oil-quenched and then drawn at various temperatures; Tables 3 and 5 give the results of static and impact tests. Here, as in other tests, the values for proportional elastic limit, ultimate tensile strength, Brinell and scleroscope hardness, and endurance limit for flexure increase or decrease together, in a general way. For the carbon-steel specimens tested there is little variation in endurance limit for flexure or in ultimate tensile strength up to a drawing temperature of nearly 600 degrees Fahr. For the nickel steel specimens both ultimate and endurance limit fall off slightly even with low temperatures of draw.

The results of Charpy tests and of repeated-impact tests do not follow those of the tension tests or of the endurance tests. As is commonly the case, Charpy tests show low results for some very moderate temperatures of draw, and both the Charpy and the repeated-impact tests give maximum values for certain temperatures of draw.

These tests suggest the importance of a careful study of the effect of heat treatment on any given steel in order to make the most effective use of the material. The range of tests given above could be greatly enlarged; the effect of water quenching, of quenching at various temperatures, of air-blast quenching without subsequent drawing, and that of double or triple heat treatments are some of the phases which immediately present themselves as subjects for careful study.

A careful heat-treatment survey of a steel would furnish the metallurgical engineer a trustworthy basis on which to determine the treatment to be given a steel to be used in a particular machine part. He must decide the relative importance of static strength, endurance strength, hardness, ductility, and ability to resist occasional shocks and overloads. Diagrams like those shown in Figs. 26 to 29, inclusive, would give him significant test data on which to base his decision as to the proper heat treatment.

Effect of Occasional Heavy Stress upon Endurance Limit.—In the first report were given the results of tests made to determine the effect of overstressing by a definite amount. A series of specimens was tested in the Farmer machine for a certain number of cycles at a unit stress above the original endurance limit. Endurance tests of these specimens were then made in the Farmer machine in the usual manner at varying stresses to determine whether the endurance limit had been affected. It was not possible in these tests to apply very severe overstress without causing the specimen to bend, thus rendering impossible a fatigue test in a rotating-beam testing machine.

The effect on the endurance limit of applying a severe overstress was studied in a series of tests in which a heavy axial tensile load was applied to each specimen a few times, and the endurance limit for this heavily overstressed material was determined by fatigue tests on these overstressed specimens. After the application of overstress, the surfaces of the specimens were not polished. In one series of tests the specimens were placed in endurance testing machines of the Farmer type a few seconds after being overstressed. In another series of tests the specimens after being overstressed were immersed in boiling water, kept there for about an hour, allowed to cool in an oven over night, and then placed in the endurance testing machine the next morning. Until stress well up toward the proportional elastic limit of the material was applied, the endurance limit of the specimens was not seriously reduced by overstressing. If a stress above the proportional elastic limit was applied, the endurance limit was reduced appreciably. For the particular steel tested the rate of diminution of endurance limit showed a marked increase as the initial axial overstress approached in magnitude the proportional elastic limit of the material. For the particular steel tested, an initial overstress seventy per cent above the original endurance limit of the metal reduced the endurance limit for subsequent reversed stress by about twenty-three per cent. No improvement of endurance limit was found in the specimens which had been placed in boiling water. These results would indicate that a severe overstress may start an incipient fatigue failure, probably at the surface of the specimen. Tests of specimens overstressed and afterwards polished might be expected to yield interesting results.

Resistance to Repeated Stress other than Reversed Stress

By F. M. Howell[*]

Introduction.—The foregoing paragraphs have been restricted to cases in which the stress in a cycle varied from a certain negative value (compression) to a positive value (tension) of the same magnitude. In many machine and structural parts stress is repeated, but not completely reversed; for example, this is the case in railroad rails, steam turbine blades and discs, wire rope without reverse bends, chain.

Special interest centers on the ranges of stress in which the maximum tensile stress is greater numerically than the maximum compressive stress, or in which the stress varies between a maximum stress and a minimum stress, both of which are tension. A special series of tests was made in which the effect of such ranges of stress was studied.

Apparatus and Test Specimens.—The machine used is shown in Fig. 30. The specimen is a cantilever beam, the shank of the specimen N being fitted tightly (to 0.001 inch) in the shaft of the machine and held in place by a set screw. The other end of the specimen carries a dead load supported by the bearing G. Mounted on the specimen and rotating with it is a spring S, fitted at each end with a pair of knife-edges at right angles K' and K'', which are designed to exert uniform tension on the specimen and at the same time to permit the specimen to bend. There is a shoulder on the specimen at F, which supports one end of the spring apparatus; the spring is compressed by tightening the nut L. The bearing G is held in place by the collar A. As the specimen rotates, the upper fibers are subjected to the maximum stress, which is the sum of the tensile stress resulting from the spring and the tensile stress due to the bending load, while the lower fibers carry the minimum stress, the *algebraic* sum of the tensile stress due to the spring and the compressive stress resulting from bending. Any desired maximum or minimum stress, or range of stress can be obtained by varying the tension and bending loads.

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The specimen found most satisfactory and now used for all tests in this machine is shown in Fig. 31. A specimen cut with a tool swung on a larger radius (9.85 inches) was used for some tests, but it was found that the specimen would very often bend when a high tensile load was used after a small number of cycles of stress. This trouble was not entirely eliminated by reducing the radius to one inch, but the results have been more satisfactory since this radius was adopted.

The loads are applied in the following manner: The specimen with the tension-spring apparatus is placed on the bed of a universal testing machine and the desired load is applied to the spring. The length of the spring is then measured with a strain-gage on three gage-lines and the nut screwed down on the specimen until it holds the spring at the desired length. Then the specimen is inserted in the tension-bending machine and the bending load applied. The bending load includes an amount, previously determined by calibration, to correct for the stiffening effect of the friction at the knife-edges.

Test Data.—The steels used for this series were selected from the steels used in the regular tests:

Steel No. 7 —3.50 Nickel—Treatment A;
Steel No. 7 —3.50 Nickel—Treatment B;
Steel No. 7 —3.50 Nickel—Treatment C;
Steel No. 7 —3.50 Nickel—Treatment D;
Steel No. 10a—0.53 Carbon—Normalized;
Steel No. 10a—0.53 Carbon—Sorbitic.

As in the tests under reversed stress, the values of stress were computed by the ordinary formulae of mechanics.

Heretofore the term *endurance limit* has been used to denote the critical stress below which the material would not fail under an indefinitely large number of cycles of *completely reversed* stress. It now becomes necessary to define the critical maximum stress for a range of stress not involving complete reversal. When critical stresses of this nature are discussed, the term *endurance limit* will be followed by a phrase, or a subscript, indicating the ratio of the minimum stress to the maximum stress, or the ratio of the value of the lower extremity of the range to that of the upper extremity. For instance, the statement that the endurance limit at a ratio of —0.5 is 96 000 pounds per square inch for a certain steel means that that steel will withstand an indefinitely large number of cycles of stress ranging from 48 000 pounds per square inch in compression to 96 000 pounds per square inch in tension. For convenience, the term *endurance limit* without a modifying phrase, or subscript, will be taken to mean the endurance limit for complete reversal of stress or a ratio of —1.0. Figs. 35 to 38, inclusive, show the *S-N* diagrams for the tests made in the tension-bending machines. In this chapter the symbol Q_r will be used to denote the ratio of the endurance limit at the ratio r to the endurance limit for complete reversal of stress, both endurance limits being those obtained from tests in the tension-bending machines; for example,

$$Q_{-0.6} = \frac{\text{endurance limit for a ratio of } -0.6}{\text{endurance limit for complete reversal}}$$

It was found that the endurance limits for reversed stress as determined by the tension-bending machines were considerably lower, in one case as much as ten per cent, than the corresponding limits obtained by the Farmer rotating-beam machine. This may be explained by the following circumstances: first, the radius of the turned-down portion of the tension-bending specimen (Fig. 31) was somewhat less than the radius of the turned-down portion of the Farmer specimen (Fig. 32); and second, with the tension-bending machine there was generally more vibration of the specimen, and, consequently, the actual stress was slightly higher than the computed value.

Inelastic Action during Tests.—In general the maximum allowable unit stress increases as the ratio of minimum to maximum stress progresses from —1.0 to 0, but there is a tendency for the curves to flatten out as they approach the proportional elastic limits of the materials (Figs. 41 to 43, inclusive). This may be due partly to the machine used for these tests, for as soon as the stress in a specimen reaches the elastic limit, excessive deflection with consequent "whipping" occurs. Thus, the stress is increased beyond the calculated value, and the specimen fails. This failure is very often a yield-point failure, not a fatigue failure. In the cases where a fatigue failure occurred at computed stresses above the proportional elastic limit, it is doubtful whether the computed stresses were maintained throughout the test, as any lengthening of the specimen would cause a decrease in the steady tensile stress and a consequent change in the minimum stress, maximum stress, and ratio of minimum to maximum.

In the case of the nickel steel with Treatment C, however, there seems to be no flattening of the curve until a point well above the yield point was reached. The same is true of Steel No. 10, 0.49 carbon, normalized. Steel No. 7, with Treatment D and the 0.49 carbon sorbitic steel, on the contrary, seem to be affected at a computed stress considerably below their proportional elastic limits. It is not strange that a ductile annealed steel, such as the nickel steel with Treatment D, should be affected at a stress lower than the proportional elastic limit, as the tensile stress-strain curve bends over gradually and the proportional elastic limit is not well defined.

Goodman Diagram for Effect of Range of Stress on Fatigue of Steel.—Wöhler concluded as the result of his experiments that steel would rupture at a unit stress much below the ultimate strength, and even below the elastic limit if the stress were repeated a sufficient number of times; that within certain limits the range of unit stress, and not the maximum stress, determined the number of repetitions for rupture. For a given maximum or minimum unit stress, the number of repetitions for rupture increases as the range of stress is diminished, and there appears to be a limiting range for which repetitions for rupture become infinite;[11] and as the maximum unit stress increases the limiting range of stress decreases.

Fig. 40 is a copy of the "dynamic theory" diagram drawn by Professor Goodman[12] of the University of Leeds, who based his diagram chiefly on the results of Wöhler's tests and some tests conducted by himself. The endurance limits were taken as the stresses at which the material withstood over 4 000 000 cycles of repeated stress. The dynamic theory assumes that varying loads produce the same effects as suddenly applied loads, that is, twice the destructive effect of slowly applied loads. It also assumes that any repeated loading may be resolved into a repeated loading superimposed on a steady loading, and that a machine part will not break under repeated loadings if the maximum effective stress (dead-load stress plus twice the repeated-load stress) does not exceed the static ultimate tensile strength of the steel.

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[11] The term "infinite" is the term used by Goodman in discussing Wöhler's results. The writers prefer the term "indefinitely large."

[12] Goodman, "Mechanics Applied to Engineering," p. 634 (9th Ed.).

In this diagram the values of the minimum stresses, or the stresses due to dead load, are plotted in terms of percentage of the static ultimate strength, forming the straight line *DOB*. The maximum values of the limiting ranges of stress were found to fall along a line *CAB*, which intersects the line *OE* at the point whose ordinate represents one-half of the static ultimate strength. The vertical distance between the lines *CAB* and *DOB* is a measure of the range of the varying stress or the stress due to the live load. Thus, for failure the dead load plus twice the live load equals the ultimate strength, which is the basis of the dynamic theory.

Discussion of Results of Tests.—The Goodman diagram for Steel No. 7, Treatment A, as well as the results obtained by the tension-bending tests on this steel, are shown in Fig. 41. The maximum unit stresses obtained in this investigation are consistently higher than the corresponding values of Goodman's diagram, and the results are not in accord with the dynamic theory. One reason for this may be that the dynamic theory diagram is based chiefly on direct tension-compression stresses; and Wöhler's tests, which were used by Goodman, were tension-compression tests, whereas in this investigation tension-bending tests were made. A few results secured for complete reversal of stress in direct tension-compression tests indicate that the endurance limit in those tests is lower than that obtained in reversed-bending tests; and it may be that direct tension-compression tests would lower the endurance limits so that they would more nearly agree with the results of Goodman. In this connection it may be noted that some tests conducted by Professor B. P. Haigh[13] apparently bear out this statement.

The Goodman diagrams for the other heat treatment of Steel No. 7 and for Steel No. 10, and the experimental results are shown in Figs. 41 to 43, inclusive. In all cases, it will be noted, the Goodman diagram gives *safe* values, that is, the ranges of stress obtained were greater than the corresponding ranges given by Goodman's diagram, but the Goodman values when used as a basis for design for parts subjected to repeated bending give working stresses lower than is necessary in most cases.

Goodman considered the endurance limit for reversed stress equal to one-third of the ultimate strength of the material, whereas in this investigation it has been found to be nearer one-half the ultimate strength for specimens subjected to bending. Moreover, it seems desirable to base the treatment of repeated stress not involving complete reversal not on the ultimate static strength, but on the endurance limit for complete reversal, since that value can be determined quite easily. Furthermore, in order to show graphically the results of tests of specimens under stress repeated but not reversed, it is convenient to plot diagrams with values of Q as ordinates and of r as abscissae; Q is the ratio of the endurance limit for various ratios of minimum stress to maximum stress to the endurance limit for complete reversal of stress, the endurance limits being those obtained from tests in the tension-bending machines; r is the ratio of minimum stress to maximum stress within a cycle. Fig. 44 shows the results of the tests plotted in this way.

In tests made on a rotating-beam type of machine it is not certain that failures are true fatigue failures when the maximum stress is above the proportional elastic limit. It has been considered best in plotting results to discard those from tests in which the computed fiber stress was as high as the lowest value found for the proportional elastic limit of the material. Moreover, since, due to the greater vibration and the sharper radius of the turned-down portion of specimens, the actual stress in the tension-bending specimens is slightly greater than the computed stress, the following procedure has been followed: For any steel the ratio between endurance limit as determined in the tension-bending machine with stress completely reversed (springs removed) and the endurance limit as determined in a Farmer rotating-beam machine was computed. This ratio is denoted by k. Then when the results of tension-bending tests were plotted, all tests were discarded for which the value of the computed stress was as high as kS_e, in which S_e is the lower limit of range of values found for the proportional elastic limit of the steel tested.

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[13] "The Endurance of Metals under Alternating Stresses," by B. P. Haigh, D. Sc. Royal Naval College, Greenwich, Journal of the West of Scotland Iron and Steel Institute, Glasgow.

Application to Design.—The test results are somewhat more erratic than those by the Farmer rotating-beam machine. However, in Fig. 44 a straight line drawn between a point whose coördinates are (+ 1.0, −1.0) and one whose coördinates are (+ 1.5, 0.0) furnishes a fairly satisfactory graph.

In designing a member which must withstand a large number of cycles of stress, the designer may use the following empirical formula, the equation of the straight line in Fig. 44, which gives values somewhat on the safe side of test results, and which shows the ratio of the endurance limit for any range of stress to the endurance limit for completely reversed stress:

$$Q_r = \frac{r+3}{2} \text{ or } S_r = S_{-1}\frac{r+3}{2}$$

in which r is the algebraic ratio of minimum stress to maximum stress during a cycle of stress,

Q_r is the ratio of endurance limit for ratio r to endurance limit for completely reversed stress,

S_r is the endurance limit for the ratio r, and

S_{-1} is the endurance limit for completely reversed stress.

This formula can be used only up to the limit at which the maximum unit stress set up reaches the proportional elastic limit of the material, and for most steel this eliminates ratios of minimum stress to maximum stress greater than zero. Beyond the proportional elastic limit the static properties of the steel are the governing factors rather than the fatigue properties.

It seems highly desirable that further tests along this line should be conducted, as the information obtained therefrom would, no doubt, be of great value to designers of parts which are to be subjected to repeated stresses not completely reversed. It is believed, however, that any further investigation should include direct tension-compression tests as well as combined tension-bending tests.

Unsolved Problems in Fatigue of Metals

Summary of Field Covered by Present Investigation.—The specific field laid out for the present investigation at its beginning was the study of general laws of fatigue for wrought ferrous metals. While much valuable work had been done in studying the fatigue of metals, it was felt that there was great need for test data on representative steels tested to reversals of stress running as high in number as one hundred million. The accumulation of such data has been the outstanding laboratory problem of this investigation. Several other laboratories also have collected many data.

All this work has, it is believed, established on a reasonably firm basis experimental criteria for judging the performance of wrought ferrous metals under repeated stress, and has fixed fairly trustworthy correlations between fatigue-resisting properties of wrought ferrous metals and other physical properties. There remain, however, a large number of unsolved problems of prime importance to users of metals.

Effect of Notches, Grooves, and Sudden Changes of Outline.—There has been presented much experimental evidence which shows clearly the marked injurious effect which notches, grooves, and sudden changes of outline of a machine part exert on its resistance to repeated stress. Sharp notches, shoulders or keyways may increase localized stresses to a value at least double that computed by the ordinary flexure formulae, and, *under the action of repeated stress,* such localized stress is effective in causing structural damage. There are no comprehensive data, however, for making any quantitive estimate of the effectiveness of fillets and other means of diminishing this localized stress. For example, it is not known whether the radius of a fillet at a shoulder of a shaft should be proportional to the diameter of the shaft, or whether a fillet of given radius is equally effective in reducing localized stress whatever the diameter of the shaft. The weakening effect of screw threads of various types, of keyways, of holes for pins, etc., would repay investigation. As localized stress at the edges of bearings of shafts is not infrequently severe, and as cutting action at such edges may also cause grooves which are a source of heavy localized stress, the investigation of this problem seems decidedly worth while.

It can hardly be over-emphasized that the ordinary formulae of the mechanics of materials neglect the existence of many localized stresses in structures and machine parts, and that under the action of repeated stress such localized stresses are sources of potential fatigue failure. The designer of machine parts must not be satisfied when he has applied the ordinary formulae of mechanics of materials and has found his computed working stresses safe; he must always be on the lookout for sources of localized stress which are neglected in using the ordinary formulae.

Effect of Flaws in Metals and of Crystalline Structure.—Available test data for the study of the effect of flaws and of varying crystalline structures in metals are even fewer than are data for the study of the effect of notches, grooves and sudden changes in section. It is generally supposed that a metal with a fine crystalline structure is more resistant to fatigue than is one with a coarse crystalline structure, and that a metal with elongated crystals, such as are found in an unannealed steel casting, is less resistant to fatigue than is a metal with rounded crystals like those in an annealed steel casting. There are, however, very few experimental data to confirm definitely the truth of either supposition. It seems reasonable to suppose that internal flaws act to weaken metal under repeated stress in a manner similar to the action of external notches and grooves, but very little experimental study has been given to this problem, and no data are available for making a comparison of the weakening effect of internal flaws and of notches, grooves and scratches. It is not known whether the correlation between ultimate tensile strength and endurance limit, which has been found for sound wrought ferrous metal, exists for metal with internal defects. At present the only test for defects is by visual examination, either with the unaided eye or with the aid of the microscope. Such examination does not yield quantitative results which can be expressed in specifications, and a study of the possibility of obtaining such quantitative results through the use of repeated-stress tests of some kind would be valuable.

Fatigue Strength of Metals at High Temperature.—There is an almost complete lack of information concerning the strength of metal subjected to repeated stress at high temperatures. Machine parts which have to withstand this combination include steam turbine blades and discs, cylinders, pistons, valves and valve springs of internal combustion engines. It is known that the static strength of metals falls off rapidly with increase of temperature, but it is not known how the endurance limit is affected. Such an investigation would call for an extensive series of tests, and would involve a considerable expense. It would be necessary to devise apparatus for holding a high temperature at a constant value for a long time. The results of an investigation of this particular problem would be of great importance.

Fatigue Strength of Cast Metals.—All the tests made during the course of the present investigation, and nearly all repeated stress tests for which records are available have been tests of rolled metal. Few test data are in existence concerning the behavior of cast metal under repeated stress. This problem is of importance in connection with the great use of steel castings in place of forgings and built-up parts, as for example, in railway car couplers and bolsters, crank shafts of pumps and engines. Cast metal has a crystalline structure radically different from that of rolled metal, and the question of the fatigue strength of cast metal is related to the question of the effect of crystalline structure on fatigue strength of metal. Gray cast iron is not often used for parts subjected to repeated stress, though cylinders of steam engines and of gas engines might be classed under this category. Malleable cast iron is occasionally used as a stress-resisting member. Some data on the strength of malleable cast iron under repeated stress has been obtained.

It is not known whether the high static strength obtainable in steel castings is accompanied by a high endurance limit or not. The effects of annealing and of other heat treatments of steel castings on the ability to withstand repeated stress are not known. The effect of the rather large shrinkage strains in some steel castings on their ability to resist repeated stress is also unknown. The study of the fatigue strength of steel castings may be characterized as one of the major unsolved problems in the fatigue of metals.

Fatigue Strength of Non-Ferrous Metals.—In the present investigation no non-ferrous metals have yet been studied. There are several investigations of *special* non-ferrous metals in progress in other laboratories. There is some indication that for certain non-ferrous metals, the endurance limit is not so clearly defined as is the case for wrought ferrous metals, and there is further indication that the correlation which seems to exist for wrought ferrous metals between ultimate tensile strength and endurance limit does not exist for these non-ferrous metals. The fatigue strength of non-ferrous metals is certainly a major problem, or rather a group of major problems, in any general investigation of the fatigue of metals.

Detection of Incipient Fatigue Action before Failure Occurs.—A question of vital importance in the investigation of the fatigue of metals is that of determining whether progressive failure of the metal has begun in any part. In the case of wire ropes bent round sheaves this question can be answered with a good degree of certainty, because long before the rope as a whole is in danger of failure, individual wires break, and these wires are usually on the outside of the rope. In parts made of solid metal, however, no such warning is given. If a crack large enough to be detected develops, the member is usually near to the point of failure.

This problem is in an almost unexplored field. There is promise that a study of the change of magnetic properties might yield a method of predicting the early stages of progressive failure for some iron or steel machine parts. A study of the transmission of waves of sound through the metal is another possible avenue of approach. This problem would require the exclusive attention of an investigator probably for a long time. Its solution would be of great value to all users and inspectors of machines.

A Testing Machine for Tests of Metals under Reversed Bending

Nearly all the tests of metals in reversed bending in this investigation have been made on the Farmer rotating-beam machine shown in Fig. 1. The specimen for this machine is shown in Fig. 32. In this machine the specimen rotates, and it is necessary to center the specimen very carefully with respect to the collets which hold it. Moreover, it is not convenient to make rise-of-temperature tests on a rotating specimen, nor is it possible to examine the specimen during the test without stopping the machine.

Fig. 33 shows a reversed-bending testing machine recently put into service, in which the above difficulties have been overcome. One end of the specimen *S* is held rigid in the vise *V*, and the other end, which runs in the bearing *B*, is rotated in a small circle. The bearing *B* is carried on gimbals. Sidewise pressure, which can be adjusted by means of a screw, is brought on the bearing *B* by a calibrated indicator spring *I*. The compression of the spring, and hence the load on the specimen, is measured by means of a strain-gage spanning the gage-holes *GG* shown near the ends of the spring. The rotating spring is carried in the cross-head *C*. Sidewise motion of the bearing *B* is prevented by placing the bearing in a slot and excessive displacement of the bearing, when the specimen breaks, by the rod *R*. The cross-head is driven by a shaft *H*, a pulley *P*, and a motor not shown in the figure. The number of revolutions of the cross-head is measured by the revolution-counter *K* which is driven by a worm on the drive-shaft *H*.

When a test to destruction is carried out, the fracture of the specimen occurs at the necked-down part *N*, and the broken end of the specimen hits a screw and kicks out the lever *L*. This releases the spring *W*, which then opens the motor switch *D*, thus stopping the machine.

This machine can be used for tests in which the rise of temperature of the specimen is measured. For this purpose fiber strips are placed between the head-stock *T* and the base *A*, between the vise *V* and the base *A*, and a fiber bushing is inserted between the end of the specimen and its bearing. A thermocouple (copper-constantan) is held against the specimen at the necked-down portion, and an opposed thermocouple is placed in an insulating bushing against the vise end of the specimen. From these couples wires lead to a delicate galvanometer. The fiber bushings serve to minimize the transfer of heat from the rotating parts of the machine.

The machine produces cycles of completely reversed bending stress, and can be run at a speed of eighteen hundred revolutions per minute. Fig. 34 shows the test specimen, which is less expensive to machine than is the long, slender Farmer specimen.

TABLE 1. CHEMICAL ANALYSES OF STEELS TESTED

Steel No.	Furnished by	Material Furnished in	CONTENT, PER CENT						
			Carbon	Chromium	Nickel	Silicon	Manganese	Phosphorus	Sulphur
1	Illinois Steel Co.	2 × 1 flats	1.20	......	......	0.19	0.25	0.021	0.021
3	John A. Roeblings Sons Co.	Billets 4-in. square.	0.52	......	......	0.24	0.56	0.037	0.029
4	John A. Roeblings Sons Co.	Billets 4-in. square.	0.37	......	......	0.16	0.58	0.032	0.035
5	Halcomb Steel Co.	2 × 1 flats	0.24	0.87	3.33	0.15	0.37	0.019	0.025
6	Carnegie Steel Co. through Standard Steel Co.	2 × $\frac{7}{8}$ flats	0.93	......	......	0.03	0.38	0.017	0.045
7	Midvale Steel & Ord. Co. through General Electric Co.	1-in. squares	0.41	0.18	3.41	0.25	0.75	0.020	0.020
9	American Rolling Mill Co.	1-in. rounds	0.02	......	......	0.02	0.03	0.005	0.042
10	Inland Steel Co.	$\frac{11}{16}$-in. squares	0.49	......	......	0.12	0.46	0.017	0.029
10a	Inland Steel Co.	$\frac{11}{16}$-in. squares	0.53	......	......	0.12	0.48	0.017	0.037

TABLE 4. RESULTS OF COMPRESSION TESTS AND TORSION TESTS

Steel No.	Steel Designation	COMPRESSION		TORSION		Endurance Limit
		Proportional Elastic Limit lb. per sq. in.	Yield Point lb. per sq. in.	Proportional Elastic Limit lb. per sq. in.	Yield Point lb. per sq. in.	Rotating-beam Machine lb. per sq. in.
1	1.20 carbon, normalized	55 300	57 900	36 500	39 700	50 000
	sorbitic	102 700	111 500	80 600	none	92 000
3	0.52 carbon, normalized	47 800	51 000	30 000	34 600	42 000
	sorbitic	84 400	87 400	52 200	none	55 000
4	0.37 carbon, normalized	36 300	38 100	20 300	22 500	33 000
5	Chrome-nickel, treatment A	122 600	130 100	72 400	84 900	68 000
	treatment B	97 800	100 000	62 500	none	65 000
	treatment C	91 500	97 400	62 300	none	67 000
	treatment D	56 000	60 800	34 200	36 300	49 000
6	0.93 carbon, pearlitic	23 500	29 700	15 600	22 500	30 500
	sorbitic	64 800	72 700	42 000	none	56 000
	troostitic	106 500	none	75 200	none	98 000
7	3.50 nickel, treatment A	102 300	109 700	64 100	74 500	64 000
	treatment B	86 400	94 000	55 500	none	63 000
	treatment C	88 100	90 500	62 000	65 800	64 000
	treatment D	59 300	63 000	38 900	43 000	54 000
9	0.02 carbon, (ingot iron)	19 200	20 600	12 500	13 600	26 000
10	0.49 carbon, normalized	39 800	43 800	27 300	30 100	33 000
	sorbitic	55 900	60 100	36 800	none	48 000

Table 2. Heat Treatments of Steels Tested

Steel No.	Steel Designation	Heat Treatment
1	1.20 carbon, normalized	Heat to 1460° F.; hold 15 min.; cool in furnace (this anneals the steel so that it can be machined); then heat to 1580° F.; hold 15 min.; cool in furnace with door open.
	sorbitic	First anneal as above; then heat to 1470° F.; quench in oil; reheat to 860° F.; hold 30 min.; cool in air.
	series II, draw A	Heat to 1460° F.; hold 20 min.; cool in furnace; reheat to 1625° F.; hold 15 min.; quench in oil.
	series II, draw B	Anneal, reheat, and quench as for draw A; then reheat to 400° F.; hold 30 min.; cool in air.
	series II, draw C	Anneal, reheat, and quench as for draw A; then reheat to 650° F.; hold 30 min.; cool in air.
	series II, draw D	Anneal, reheat, and quench as for draw A; then reheat to 925° F.; hold 30 min.; cool in air.
	series II, draw E	Anneal, reheat, and quench as for draw A; then reheat to 1200° F.; hold 30 min.: cool in air.
	series II, draw F	Anneal, reheat, and quench as for draw A; then reheat to 1400° F.; hold 30 min.; cool in air.
3	0.52 carbon, normalized	Heat to 1550° F.; hold 15 min.; cool in air.
	sorbitic	Normalize as above; reheat to 1450° F.; hold 15 min.; quench in water; reheat to 1200° F.; cool in air.
4	0.37 carbon, normalized	Heat to 1495° F.; hold 15 min.; cool in furnace with door open.
	sorbitic	Heat to 1550° F.; hold 15 min.; quench in water; reheat to 1050° F.; cool in air.
5	Chrome-nickel, treatment A	Steel received annealed; heat to 1525° F.; quench in oil; reheat to 700° F.; quench in oil.
	treatment B	Steel received annealed; heat to 1525° F.; hold 30 min.; quench in oil; reheat to 1450° F.; quench in oil; reheat to 1200° F.; hold 1 hour; cool in furnace.
	treatment C	Steel received annealed; heat to 1525° F.; hold 30 min.; quench in oil; reheat to 1450° F.; quench in oil; reheat to 1200° F.; hold 1 hour; quench in water.
	treatment D	Steel received annealed; heat to 1525° F.; hold 30 min.; cool in air; reheat to 1450° F.; hold 30 min.; cool in furnace.
6	0.93 carbon, normalized	Heat to 1600° F.; hold 15 min.; cool in air.
	pearlitic	Normalize as above; reheat to 1450° F.; hold 15 min.; cool in furnace.
	sorbitic	Normalize as above; reheat to 1450° F.; hold 15 min.; quench in oil; reheat to 1200° F.; hold 30 min.; cool in air.
	troostitic	Normalize as above; reheat to 1450° F.; hold 15 min.; quench in oil; reheat to 850° F.; hold 30 min.; cool in air.
7	3.50 nickel, treatment A	Heat to 1525 °F.; hold 30 min.; cool in furnace; reheat to 1525° F.; hold 15 min.; quench in oil; reheat to 1100° F.; hold 2 hours; cool in furnace.
	treatment B	Anneal as for treatment A; reheat to 1525° F.; hold 15 min.; quench in oil; reheat to 1200° F.; hold 2 hours; cool in furnace.

Table 2. Heat Treatments of Steels Tested—(Continued)

Steel No.	Steel Designation	Heat Treatment
7	3.50 nickel, treatment C	Anneal as for treatment A; reheat to 1490° F.; hold 15 min.; quench in water to 930° F., introduce into hot soaking bath; as soon as temp. of furnace is reduced to temp. of steel put steel into furnace and reheat slowly to 1100° F.; hold 1 hour; cool in furnace.
	treatment D	Heat to 1145° F.; hold 1 hour; cool in furnace.
	series III, draw AA	Anneal as for treatment A; heat to 1450° F.; hold 15 min.; quench in oil; no draw.
	series III, draw BB	Anneal, reheat, and quench as for draw AA; reheat to 400° F.; hold 30 min.; cool in air.
	series III, draw CC	Anneal, reheat, and quench as for draw AA, reheat to 600° F.; hold 30 min.; cool in air.
	series III, draw DD	Anneal, reheat, and quench as for draw AA, reheat to 800° F.; hold 30 min.; cool in air.
	series III, draw EE	Anneal, reheat, and quench as for draw AA, reheat to 1000° F.; hold 30 min.; cool in air.
	series III, draw FF	Anneal, reheat, and quench as for draw AA, reheat to 1200° F.; hold 30 min.; cool in air.
9	0.02 carbon (ingot iron)	Tested as received (normalized).
10	0.49 carbon, normalized	Heat to 1700° F.; hold 20 min.; cool in air.
	sorbitic	Normalize as above; reheat to 1425° F.; quench in water; reheat to 1200° F.; cool in furnace.
	series I, draw A	Normalize as above; reheat to 1450° F.; hold 15 min.; quench in oil.
	series I, draw B	Normalize, reheat, and quench as for draw A; reheat to 600° F.; hold 30 min.; cool in air.
	series I, draw C	Normalize, reheat, and quench as for draw A; reheat to 800° F.; hold 30 min.; cool in air.
	series I, draw D	Normalize, reheat, and quench as for draw A; reheat to 1000° F.; hold 30 min.; cool in air.
	series I, draw E	Normalize, reheat, and quench as for draw A; reheat to 1200° F.; hold 30 min.; cool in air.
	series I, draw F	Normalize, reheat, and quench as for draw A; reheat to 1400° F.; hold 30 min.; cool in air.
10a	0.53 carbon, series Ia, draw A	Same treatment as for draw A, steel No. 10.
	series Ia, draw AA	Normalize, reheat, and quench as for draw A, steel No. 10; reheat to 400° F.; hold 30 min.; cool in air.
	series Ia, draw B	Same treatment as for draw B, steel No. 10.
	series Ia, draw C	Same treatment as for draw C, steel No. 10.
	series Ia, draw D	Same treatment as for draw D, steel No. 10.
	series Ia, draw E	Same treatment as for draw E, steel No. 10.
	series Ia, draw F	Same treatment as for draw F, steel No. 10.

TABLE 3. RESULTS OF TENSION TESTS

Steel No.	Steel Designation	Proportional Elastic Limit lb.per sq.in.	Yield Point lb.per sq.in.	Ultimate Tensile Strength lb.per sq.in.	Elongation in 2 in. Per cent	Reduction of Area Per cent	Endurance Limit Rotating-Beam Machine lb.per sq.in.
1	1.20 carbon, normalized...	58 600	60 700	116 900	7.9	11.6	50 000
	sorbitic......	120 400	130 100	179 900	9.0	15.2	92 000
	draw A......	137 500	none	220 000	0.8	2.4	105 000
	draw B......	140 500	none	224 000	2.0	3.2	107 000
	draw C......	136 000	none	224 500	3.5	6.0	108 000
	draw D.....	133 000	none	216 500	3.3	3.6	103 000
	draw E......	96 000	96 700	138 500	9.5	12.2	68 000
	draw F......	71 000	71 500	118 000	14.3	17.5	53 500
3	0.52 carbon, normalized...	45 400	47 600	98 000	24.4	41.7	42 000
	sorbitic......	80 300	84 300	111 400	21.9	56.6	55 000
4	0.37 carbon, normalized...	34 500	34 900	71 900	29.4	53.5	33 000
	sorbitic......	61 500	63 100	94 200	25.0	63.0	45 000
5	Chrome-nickel,treatmentA	115 500	128 100	138 700	18.2	61.8	68 000
	treatment B	101 700	103 700	113 300	24.2	68.7	65 000
	treatment C	86 200	100 500	114 200	23.2	69.3	67 000
	treatment D	56 700	59 800	87 300	32.9	67.1	49 000
6	0.93 carbon, pearlitic.....	28 000	33 400	84 100	24.8	37.2	30 500
	sorbitic......	60 300	67 600	115 000	23.0	39.6	56 000
	troostitic....	97 200	none	188 300	9.9	29.3	98 000
7	3.50 nickel, treatment A..	108 200	108 700	123 300	22.6	59.2	64 000
	treatment B..	82 400	91 100	111 800	23.6	60.2	63 000
	treatment C..	93 000	94 200	117 500	21.1	60.1	64 000
	treatment D..	60 800	64 600	101 600	25.5	52.2	54 000
	draw AA.....	148 000	none	294 200	6.0	47.7	120 000*
	draw BB.....	174 000	none	282 000	8.2	48.7	112 000*
	draw CC.....	189 000	196 400	226 100	7.3	56.4	98 000
	draw DD.....	155 000	158 800	172 900	9.2	57.3	89 000
	draw EE.....	131 000	135 800	148 500	12.8	57.6	78 000
	draw FF.....	72 300	86 600	121 600	16.5	60.6	65 000
9	0.02 carbon (ingot iron)...	16 100	19 000	42 400	48.3	76.2	26 000
10	0.49 carbon, normalized...	44 700	47 100	91 500	26.5	39.5	33 000
	sorbitic......	67 700	69 700	96 900	23.5	57.8	48 000
	draw A......	72 000	80 900	126 500	12.5	52.2	65 000
	draw B......	73 300	80 800	126 800	11.5	52.3	68 000
	draw C......	75 800	78 800	121 800	11.3	50.9	64 000*
	draw D......	67 700	70 500	106 900	16.8	59.5	57 000
	draw E......	62 000	65 100	94 300	18.5	64.1	50 000
	draw F......	49 000	52 000	85 600	23.5	55.3	37 000
10a	0.53 carbon, draw A......	75 000	83 200	129 300	12.0	51.7	67 000
	draw AA....	77 000	86 200	134 000	10.8	50.9	68 000
	draw B......	76 700	81 500	129 100	10.8	51.2	67 000
	draw C......	79 700	85 300	129 300	11.5	48.8	65 000
	draw D......	72 000	74 000	110 600	14.4	58.3	59 000
	draw E......	62 300	64 800	95 500	20.0	65.1	53 000
	draw F......	51 300	53 600	88 900	22.3	53.2	39 000

* Estimated from tests of at least four specimens.

TABLE 5. RESULTS OF CHARPY (NOTCHED-BAR), REPEATED-IMPACT AND HARDNESS TESTS

Steel No.	Steel Designation	Charpy (Notched-bar) Test ft.-lb.	Repeated-Impact Test		Brinell Hardness No.	Scleroscope No.	Endurance Limit
			No. of Double Blows	Total Energy ft.-lb.			Rotating-beam Machine lb. per sq. in.
1	1.20 carbon, normalized	1.9	39	26.0	224	31	50 000
	sorbitic	2.0	172	114.7	369	45	92 000
	draw A	2.0	....	....	444	47	105 000
	draw B	.2	....	....	426	44	107 000
	draw C	0.7	....	....	433	38	108 000
	draw D	1.3	....	....	398	36	103 000
	draw E	2.5	29	19.3	263	25	68 000
	draw F	4.8	35	23.3	224	22	53 500
3	0.52 carbon, normalized	13.2	275	183.3	193	24	42 000
	sorbitic	21.4	486	324.0	227	30	45 000
4	0.37 carbon, normalized	15.8	183	122.0	132	18	33 000
	sorbitic	....	503	335.3	....	....	45 000
5	Chrome-nickel, treatment A	45.4	1073	715.3	291	36	68 000
	treatment B	53.8	714	476.0	247	28	65 000
	treatment C	56.0	722	481.3	246	29	67 000
	treatment D	49.5	337	224.7	167	22	49 000
6	0.93 carbon, pearlitic	2.2	66	44.0	162	23	30 500
	sorbitic	3.3	128	85.3	227	31	56 000
	troostitic	4.4	227	151.3	380	51	98 000
7	3.50 nickel, treatment A	36.2	590	393.3	248	30	64 000
	treatment B	41.0	524	349.3	242	28	63 000
	treatment C	30.9	569	379.3	252	33	64 000
	treatment D	23.4	261	174.0	194	22	54 000
	draw AA	4.4	....	....	522	58	120 000*
	draw BB	17.6	....	....	488	51	112 000*
	draw CC	6.9	446	297.3	433	46	98 000
	draw DD	25.4	1761	1174.0	356	40	89 000
	draw EE	31.9	977	651.3	309	35	78 000
	draw FF	47.6	542	361.3	242	26	65 000
9	0.02 carbon (ingot iron)	19.3	260	173.3	69	18	26 000
10	0.49 carbon, normalized	14.1	196	130.7	164	21	33 000
	sorbitic	22.5	319	212.7	197	23	48 000
	draw A	23.8	702	468.0	228	31	65 000
	draw B	30.4	879	586.0	222	27	68 000
	draw C	14.1	774	516.0	217	25	64 000*
	draw D	32.1	540	360.0	205	21	57 000
	draw E	34.1	439	292.7	180	19	50 000
	draw F	23.6	219	146.0	125	17	37 000
10a	0.53 carbon, draw A	11.9	657	438.0	266	34	67 000
	draw AA	8.4	688	458.7	259	29	68 000
	draw B	14.8	734	489.3	258	27	67 000
	draw C	11.3	664	442.7	247	26	65 000
	draw D	22.5	552	368.0	224	25	59 000
	draw E	30.3	434	289.3	192	21	53 000
	draw F	19.9	224	149.3	131	18	39 000

* Estimated from tests of at least four specimens.

TABLE 6. ENDURANCE LIMITS (REVERSED STRESS) BY VARIOUS METHODS

Steel No.	Steel Designation	Reversed Bending				Reversed Torsion		Brinell Hardness No.
		Rotating-beam Machine		Rise of Temperature Test	Upton-Lewis Machine	Olsen-Foster Machine	Illinois Machine	
		Farmer Machine	Tension-bending Machine (No Tension)					
		lb. per sq. in.						
1	1.20 carbon, normalized	50 000	....	43 000	45 000	24 500	....	224
	sorbitic	92 000	....	88 000	....	....	....	369
	draw A	105 000	....	107 500	....	....	....	444
	draw B	107 000	....	107 000	....	....	....	426
	draw C	108 000	....	105 000	....	....	....	433
	draw D	103 000	....	103 000	....	....	....	398
	draw E	68 000	....	70 000	....	....	....	263
	draw F	53 500	....	49 400	....	....	....	224
3	0.52 carbon, normalized	42 000	....	41 500	32 000	....	....	193
	sorbitic	55 000	....	53 000	44 000	31 500	....	227
4	0.37 carbon, normalized	33 000	....	31 000	30 000	16 000	....	132
	sorbitic B	45 000	....	49 000	....	....	....	......
5	Chrome-nickel, treatment A	68 000	....	66 000	52 000	38 000	....	291
	treatment B	65 000	....	65 000	46 000	31 500	....	247
	treatment C	67 000	....	70 000	50 000	34 000	....	246
	treatment D	49 000	....	46 500	....	....	....	167
6	0.93 carbon, pearlitic	30 500	....	28 500	28 500	16 300	....	162
	sorbitic	56 000	....	53 000	44 000	29 000	....	227
	troostitic	98 000	....	90 000	69 000	52 000	....	380
7	3.50 nickel, treatment A	64 000	60 000	64 000	53 000	37 000	35 000	248
	treatment B	63 000	....	62 500	46 000	36 000	34 500	242
	treatment C	64 000	61 000*	61 500	....	....	....	252
	treatment D	54 000	49 000	53 500	45 000	29 000	....	194
	draw AA	120 000*	....	....	....	....	....	522
	draw BB	112 000*	....	115 000	....	....	....	488
	draw CC	98 000	....	90 000	....	....	....	433
	draw DD	89 000	....	83 000	....	....	....	356
	draw EE	78 000	....	85 000	....	....	....	309
	draw FF	65 000	....	70 000	....	....	....	242
9	0.02 carbon (ingot iron)	26 000	....	26 000	23 000	12 500	....	69
10	0.49 carbon, normalized	33 000	33 000	33 500	28 000	....	....	164
	sorbitic	48 000	....	48 000	39 000	26 000	30 000	197
	draw A	65 000	....	....	....	....	....	228
	draw B	68 000	....	63 000	....	....	....	222
	draw C	64 000*	....	....	....	....	....	217
	draw D	57 000	....	59 500	....	....	....	205
	draw E	50 000	....	52 000	....	....	....	180
	draw F	37 000	....	33 500	....	....	....	125
10a	0.53 carbon, draw A	67 000	....	63 000	....	....	....	266
	draw AA	68 000	....	64 000	....	....	....	259
	draw B	67 000	....	64 000	....	....	....	258
	draw C	65 000	....	63 000	....	....	....	247
	draw D	59 000	....	58 500	....	....	....	224
	draw E	53 000	....	53 000	....	....	....	192
	draw F	39 000	....	....	....	....	....	131

* Estimated from tests of at least four specimens.

TABLE 7. SPECIAL LONG-TIME REVERSED-STRESS TESTS OF THREE SPECIMENS

Steel No.	Steel Designation	Endurance Limit of Steel from Series of Tests	Unit Stress on Specimen for Special Long-time Run	Number of Cycles	Remarks
		lb. per sq. in.			
3	0.52 carbon, sorbitic..........	55 900	55 700	222 119 000	Broke
3	0.52 carbon, sorbitic..........	55 000	55 600	948 019 300	Broke
10	0.49 carbon, normalized.......	33 000	32 900	1000 000 000	Not broken

TABLE 9. EFFECT OF SPEED OF STRESS REVERSAL ON ENDURANCE LIMIT (Farmer Machine)

Steel No.	Steel Designation	Endurance Limit, lb .per sq. in.		
		200 r.p.m.	1500 r.p.m.	5000 r.p.m.
1	1.20 carbon, normalized......................	48 500*	50 000	50 000
1	1.20 carbon, draw D..........................	100 000	103 000	....
5	Chrome-nickel, treatment B..................	64 500	65 000	....
7	3.50 nickel treatment C......................	65 000	64 000	....
7	3.50 nickel, treatment D.....................	51 000*	54 000	....
7	3.50 nickel, draw DD.........................	86 000*	89 000	....
7	3.50 nickel, draw EE.........................	78 000	78 000	....
7	3.50 nickel, draw FF.........................	65 000	65 000	....
9	0.02 carbon, as received.....................	24 200	26 000	26 300
10	0.49 carbon, sorbitic........................	45 000	48 000	....

* Estimated from tests of at least four specimens.

TABLE 10. RESULTS OF ENDURANCE TESTS OF OVERSTRESSED STEEL

All specimens were from bars of Steel No. 10, 0.49 carbon, sorbitic. For this steel, the proportional elastic limit is 67 700 lb. per sq. in., the yield point is 69 700 lb. per sq. in., and the ultimate tensile strength is 96 900 lb. per sq. in.

Axial Tensile Stress Applied 20 Times before Placing Specimen in Endurance Testing Machine lb. per sq. in.	Per Cent above Original Endurance Limit	Specimens Placed in Endurance Machine Immediately after Axial Tensile Stress		Specimens Placed in Boiling Water and Rested Over Night before Endurance Test		Specimens Rested Three Months before Endurance Test	
		Endurance Limit lb. per sq. in.	Reduction of Original Endurance Limit per cent	Endurance Limit lb. per sq. in.	Reduction of Original Endurance Limit per cent	Endurance Limit lb. per sq. in.	Reduction of Original Endurance Limit per cent
None..................	0	48 000	0.0	......	....	......	....
55 200................	15	45 000	6.2	46 000	4.2	47 000	2.1
62 400................	30	48 000	0.0	47 000	2.1	47 000	2.1
67 200................	40	40 000	16.7	40 000*	16.7	39 000	18.8
72 000................	50	37 000	22.9	40 000	16.7	39 000	18.8
81 600................	70	37 000	22.9	37 000	22.9	39 000	18.8

* Estimated from tests of at least four specimens.

TABLE 8. RESULTS OF TESTS ON SPECIMENS RETESTED AFTER WITHSTANDING 100 000 000 OR MORE CYCLES OF REVERSED STRESS NEAR ORIGINAL ENDURANCE LIMIT

Steel No.	Steel Designation	Endurance Limit lbs. per sq. in.	Specimen No.	Unit Stress lbs. per sq. in.	Number of Cycles	% Increase of Stress above Endurance Limit
1	1.20 carbon, normalized........	50 000	1E65A	49 700	101 318 700*	....
				53 000	601 500	6.0
			1AOC	49 700	103 596 100*	....
				51 500	855 900	3.0
4	0.37 carbon, normalized........	33 000	4B13I	33 900	106 588 200*	....
				36 200	100 326 400*	9.7
				40 000	1 068 000	21.2
			4A32D	33 900	107 568 900*	....
				35 100	52 737 300*	6.4
				37 000	50 294 100*	12.1
				38 500	53 929 700*	16.7
				40 000	57 932 100*	21.2
				41 500	50 360 000*	25.8
5	Chrome-nickel, treatment A.....	68 000	5C117A	68 800	99 908 000*	....
				70 800	393 000	4.1
			5B91A	68 200	109 451 900*	....
				72 200	247 700	6.2
			5D26A	67 800	100 735 100*	....
				69 200	85 208 800	1.8
5	Chrome-nickel, treatment D....	49 000	5J91B	47 900	100 402 300*	....
				51 500	21 367 600	5.1
			5J91G	49 000	103 081 700*	....
				50 000	278 600	2.0
6	0.90 carbon, sorbitic............	56 000	6F13C	56 000	100 000 000*	....
				59 500	373 100	6.2
			6D91A	56 200	104 094 800*	....
				57 800	102 974 000*	3.2
				59 500	21 674 100	6.2
7	3.50 nickel, treatment C........	64 000	7JJ78C	60 300	15 523 800*	....
				66 100	33 447 300	3.3
			7JJ78B	63 000	15 038 300*	....
				65 100	84 040 900	1.7
9	0.02 carbon, as received........	26 000	9H65	25 900	100 409 100*	....
				26 800	55 230 100*	3.1
				27 700	50 437 200	6.5
10	0.49 carbon, series I, draw A....	65 000	10S0B	64 800	12 928 000*	....
				69 000	266 100	6.2
10	0.49 carbon, series I, draw B....	68 000	10S13D	65 100	11 137 200*	....
				69 000	13 285 400*	1.5
10	0.49 carbon, series I, draw F....	37 000	10S130B	37 000	15 544 200*	....
				46 100	115 300	24.6
			10S91A	34 800	10 122 400*	....
				38 100	10 493 200*	3.0
10a	0.53 carbon, series Ia, draw B...	67 000	10T26B	67 300	10 112 700*	....
				69 000	10 784 100*	3.0
10a	0.53 carbon, series Ia, draw C...	65 000	10R169A	64 500	24 184 200*	....
				65 500	10 902 700*	0.8
10a	0.53 carbon, series Ia, draw E...	53 000	10R130A	53 000	16 866 700*	....
				54 000	10 977 500*	1.9
10a	0.53 carbon, series Ia, draw F...	39 000	10R195B	38 100	19 826 600*	....
				45 900	459 600	17.7

* Specimen did not fail.

TABLE 11. ENDURANCE LIMITS FOR VARIOUS COMBINATIONS OF TENSILE AND REVERSED-BENDING STRESSES

Steel No.	Steel Designation	Maximum Unit Stress	Minimum Unit Stress‡	Range of Unit Stress	Ratio of Min. Stress to Max. Stress r	Ratio of Max. Unit Stress to Endurance Limit for Complete Reversal Q	Proportional Elastic Limit	Yield Point	Ultimate Tensile Strength
		lb. per sq. in.					lb. per sq. in.		
7	3.50 nickel, treatment A.	60 000	—60 000	120 000	—1.0	1.00	108 200	108 700	123 300
		68 000	—54 400	122 400	—0.8	1.13			
		66 000	—44 000	110 000	—0.67	1.10			
		83 000	—33 200	116 200	—0.4	1.38			
		96 000	0	96 000	0.0	1.60			
		100 000	28 600	71 400	0.29	1.67†			
		101 000	50 500	50 500	0.5	1.68†			
7	3.50 nickel, treatment B.	60,000*	—60 000*	120 000*	—1.0	1.00	82 400	91 100	111 800
		68 000	—45 300	113 300	—0.67	1.13			
		81 000	—32 400	113 400	—0.4	1.35†			
		83 000	0	83 000	0.0	1.38†			
		81 000	23 100	57 900	0.29	1.35†			
		88 000	44 000	44 000	0.5	1.47†			
7	3.50 nickel treatment C.	61 000*	—61 000*	122 000*	—1.0	1.00	93 000	94 200	117 500
		66 000	—52 800	118 800	—0.8	1.08			
		72 000	—43 200	115 200	—0.6	1.18			
		86 000*	—34 400*	120 400*	—0.4	1.41†			
		96 000	—19 200	115 200	—0.2	1.57†			
		99 000	0	99 000	0.0	1.62†			
		101 000*	50 500*	50 500*	0.5	1.66†			
7	3.50 nickel treatment D.	49 000	—49 000	98 000	—1.0	1.00	60 800	64 600	101 600
		48 000	—43 200	91 200	—0.9	0.98			
		52 000	—41 600	93 600	—0.8	1.06			
		54 000	—21 600	75 600	—0.4	1.10†			
		53 000	—10 600	63 600	—0.2	1.08†			
		56 000	0	56 000	0.0	1.14†			
		68 000	19 400	48 600	0.29	1.39†			
10a	0.53 carbon, normalized..	33 000	—33 000	66 000	—1.0	1.00	44 700	47 100	91 500
		36 000	—21 600	57 600	—0.6	1.09			
		47 000	0	47 000	0.0	1.42†			
		60 000*	12 000*	48 000*	0.2	1.82†			
		69 000	34 500	34 500	0.5	2.09†			
10a	0.53 carbon sorbitic.....	48 000*	—48 000*	96 000*	—1.0	1.00	67 700	69 700	96 900
		55 000	—36 700	91 700	—0.67	1.15			
		62 000	—24 800	86 800	—0.4	1.29			
		65 000	0	65,000	0.0	1.35†			
		66 000	18 900	47 100	0.29	1.37†			

* Estimated from tests of at least four specimens.
† Not plotted in Fig. 44.
‡ Minus sign in this column signifies compression.

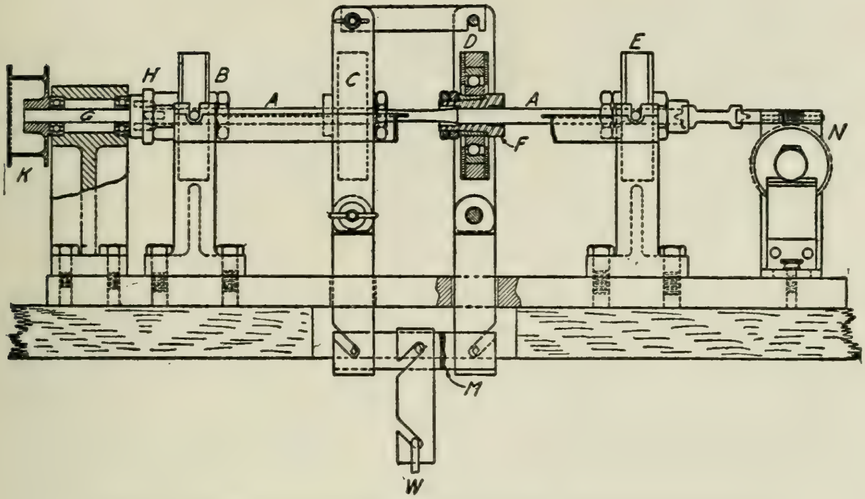

Fig. 1. Diagram of Rotating-Beam Testing Machine (Farmer)

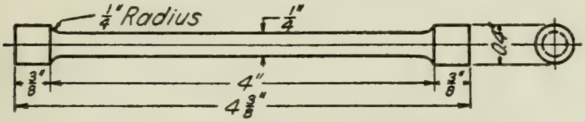

Fig. 2. Small Tension Test Specimen

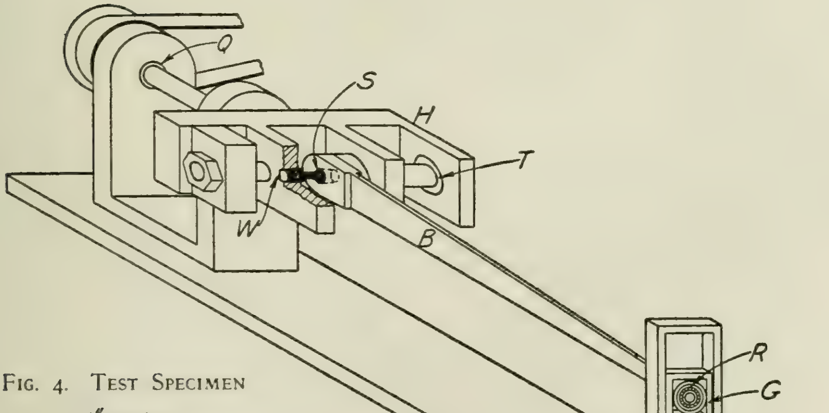

Fig. 4. Test Specimen

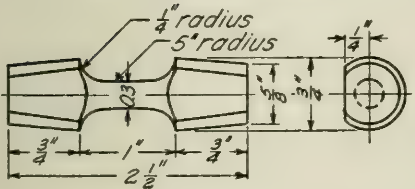

Fig. 3. Diagram of Illinois Reversed-Torsion Testing Machine

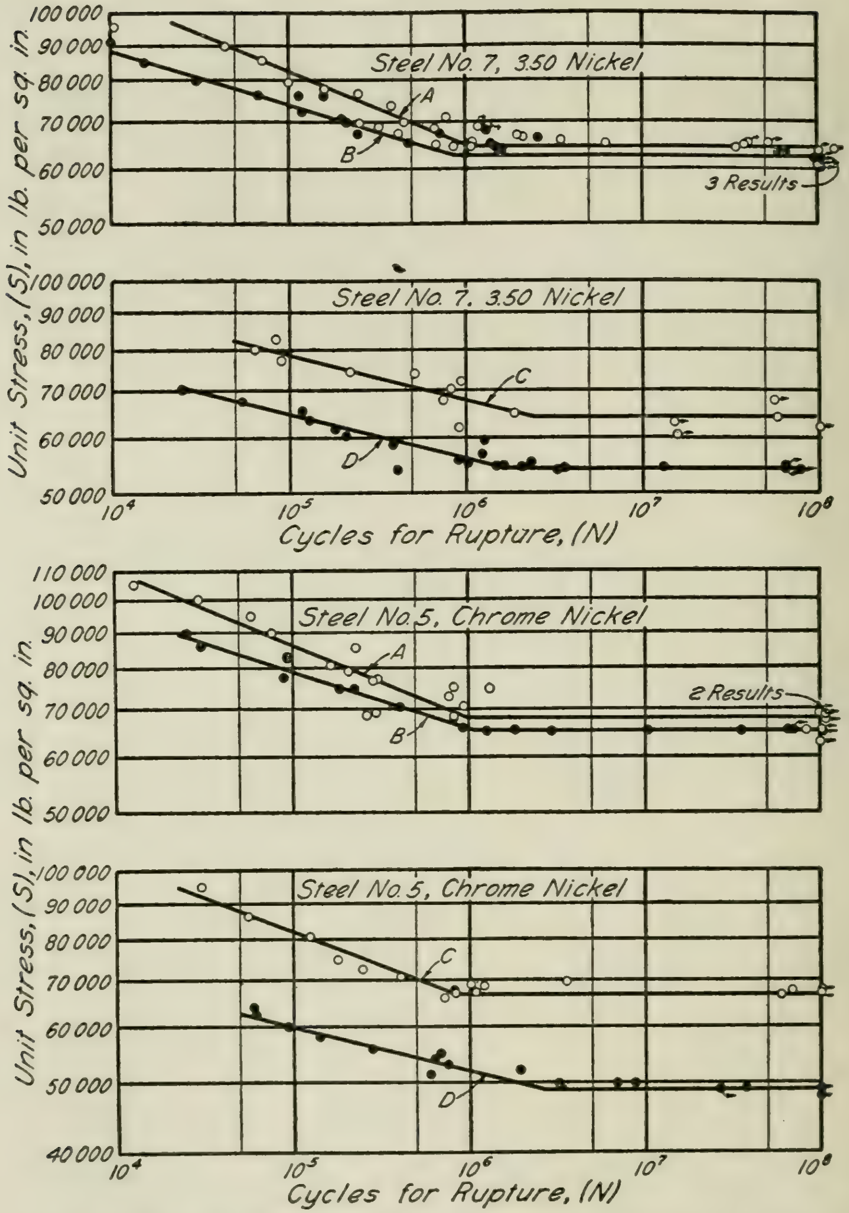

FIG. 5. *S-N* DIAGRAMS FOR 3.50 NICKEL STEEL AND CHROME-NICKEL STEEL, ROTATING-BEAM TESTS

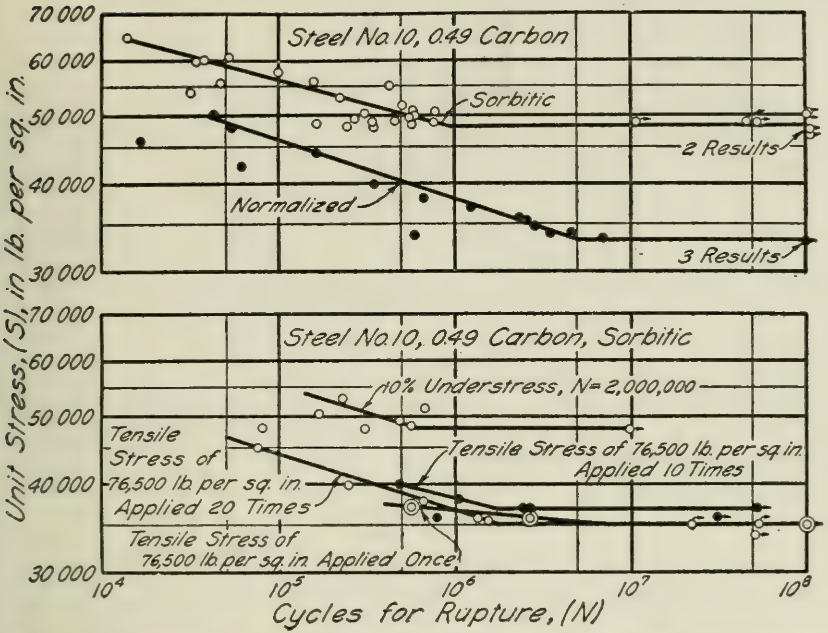

FIG. 6. *S-N* DIAGRAMS FOR 0.49 CARBON STEEL, SHOWING EFFECT OF UNDERSTRESS AND OF REPEATED APPLICATIONS OF STATIC TENSILE OVERSTRESS, ROTATING-BEAM TESTS

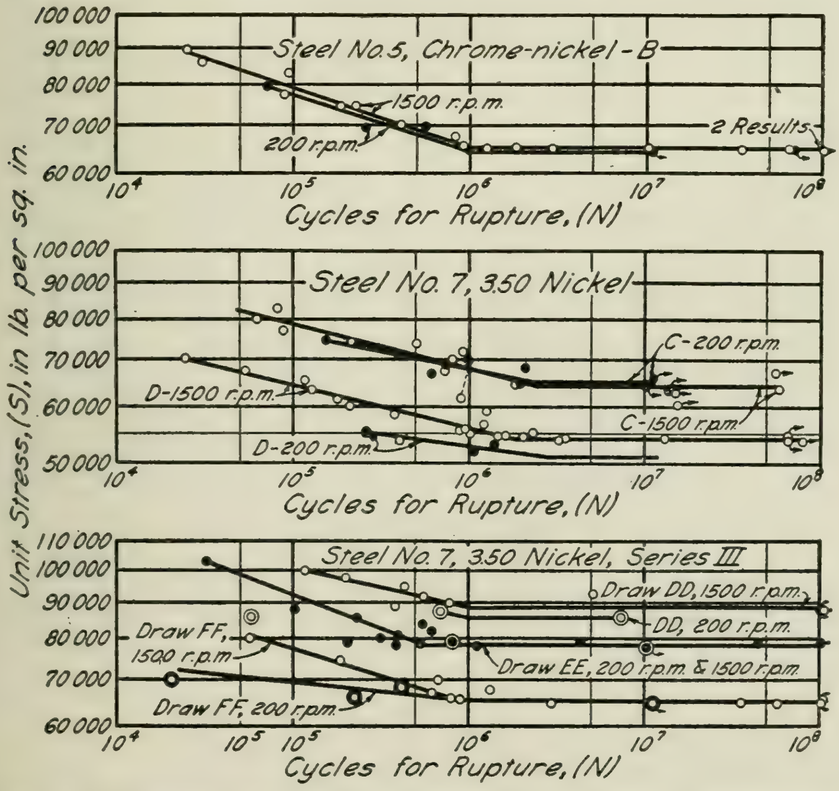

FIG. 7. *S-N* DIAGRAMS FOR EFFECT OF SPEED OF STRESS REVERSAL, CHROME-NICKEL STEEL, AND 3.50 NICKEL STEEL, ROTATING-BEAM TESTS

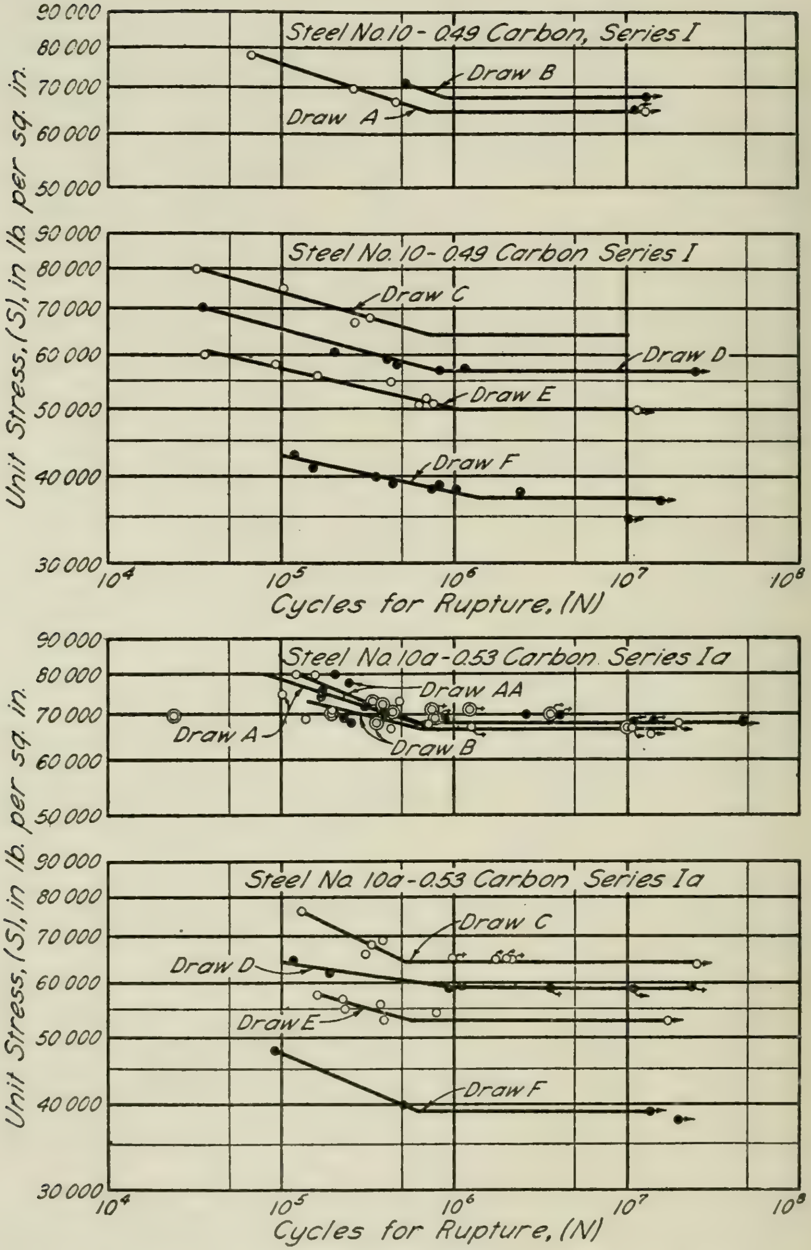

Fig. 8. S-N Diagrams for Heat-Treatment Series I, 0.49 Carbon Steel, and for Heat-Treatment Series Ia, 0.53 Carbon Steel, Rotating-Beam Tests

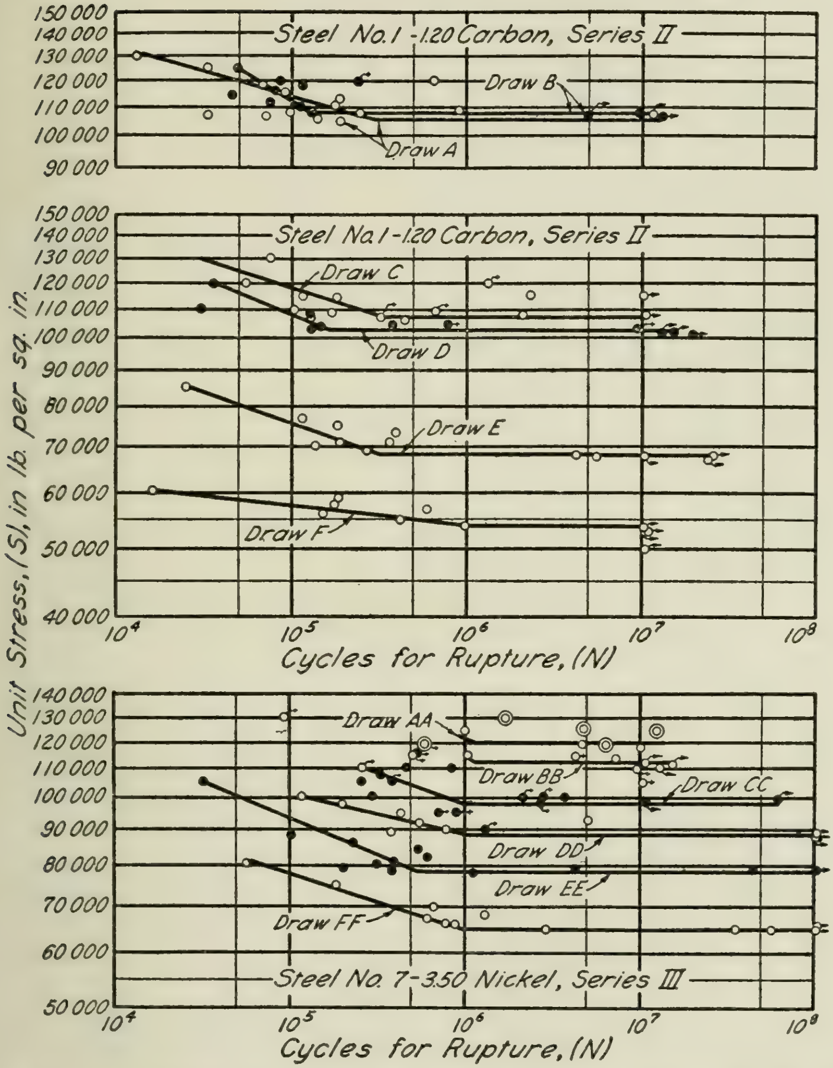

FIG. 9. S-N DIAGRAMS FOR HEAT-TREATMENT SERIES II, 1.20 CARBON STEEL, AND FOR HEAT-TREATMENT SERIES III, 3.50 NICKEL STEEL, ROTATING-BEAM TESTS

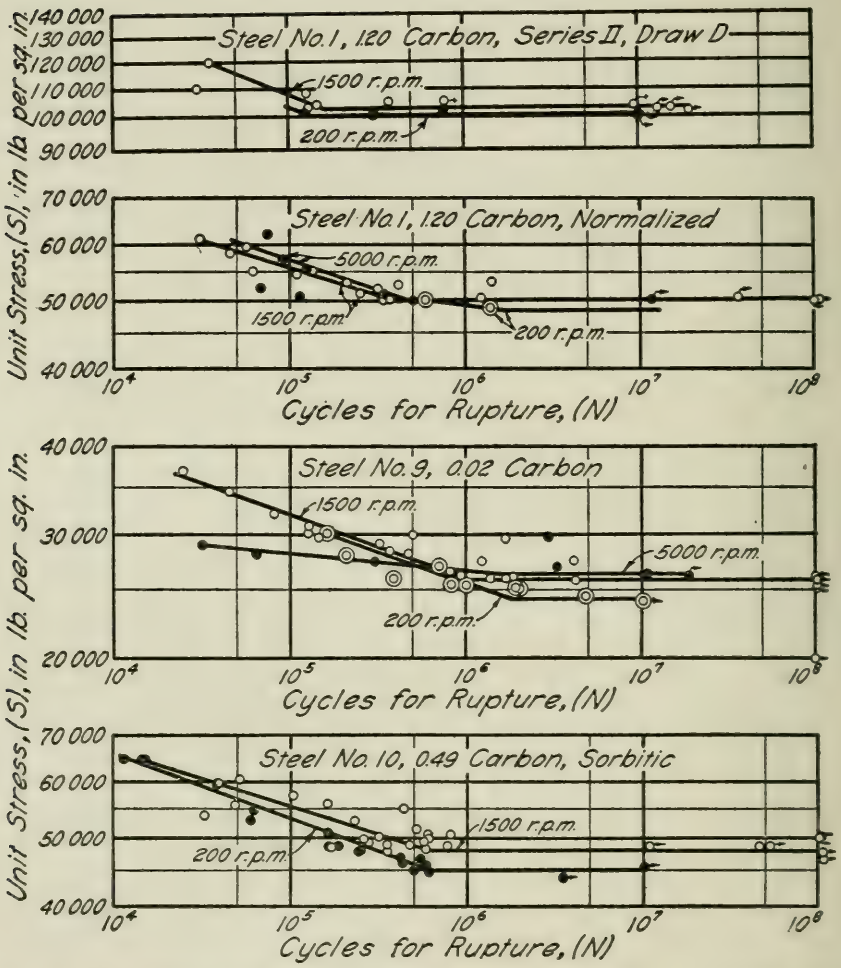

FIG. 10. *S-N* DIAGRAMS FOR EFFECT OF SPEED OF STRESS REVERSAL, 1.20 CARBON STEEL, 0.02 CARBON STEEL, AND 0.49 CARBON STEEL, ROTATING-BEAM TESTS

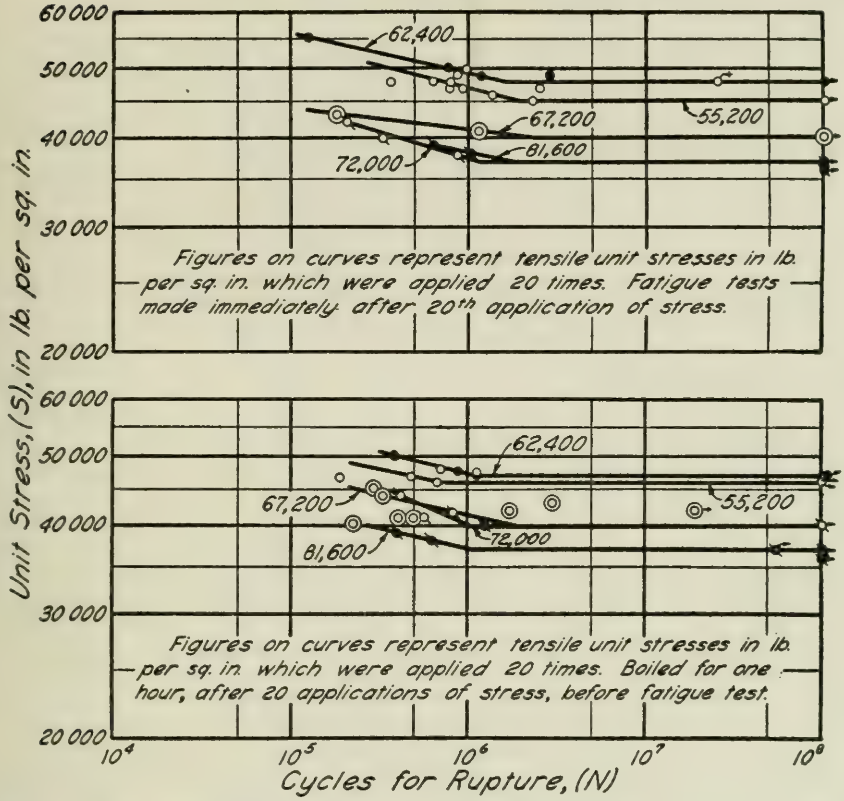

Fig. 11. *S-N* Diagrams for Effect of Repeated Applications of Static Tensile Overstress, Rotating-Beam Tests, Steel No. 10, 0.49 Carbon

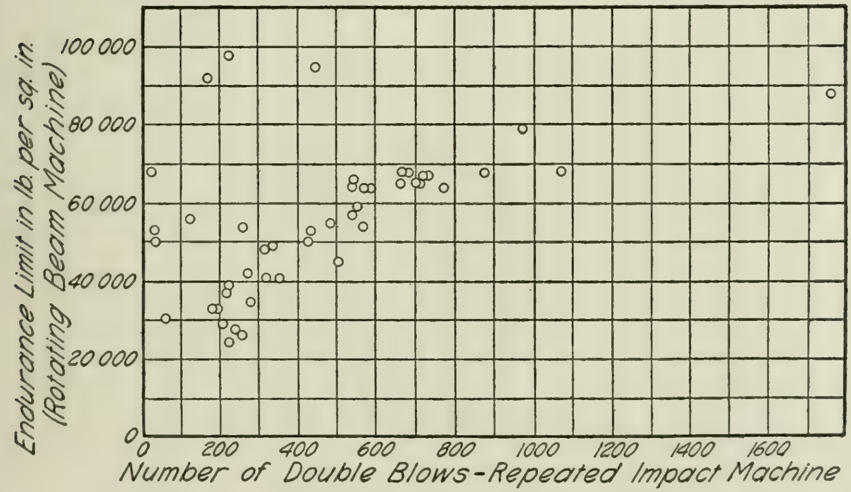

Fig. 12. Correlation of Endurance Limit with Repeated-Impact Results

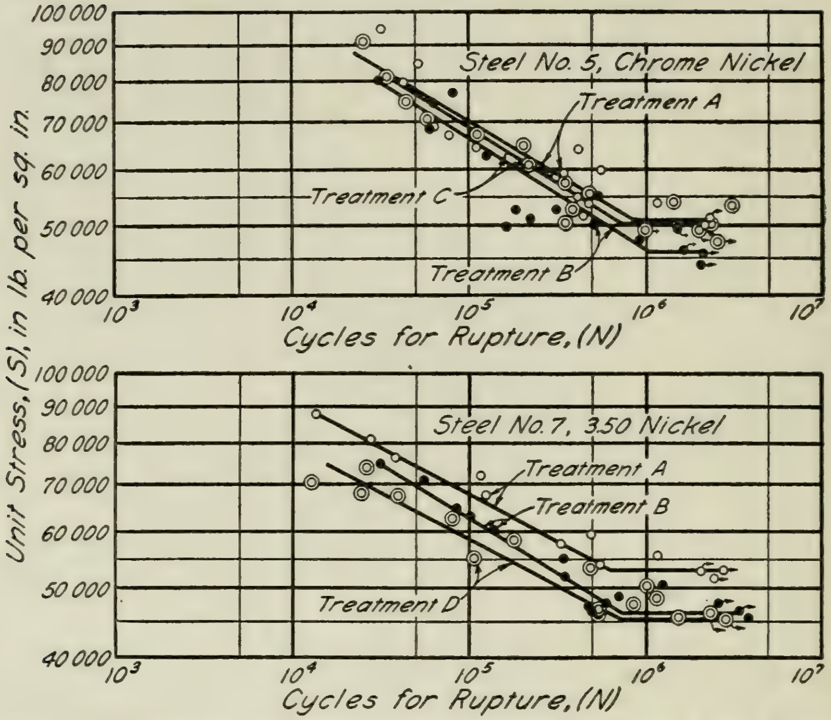

Fig. 13. *S-N* Diagrams for Chrome-Nickel Steel and 3.50 Nickel Steel, Upton-Lewis Reversed-Bending Tests

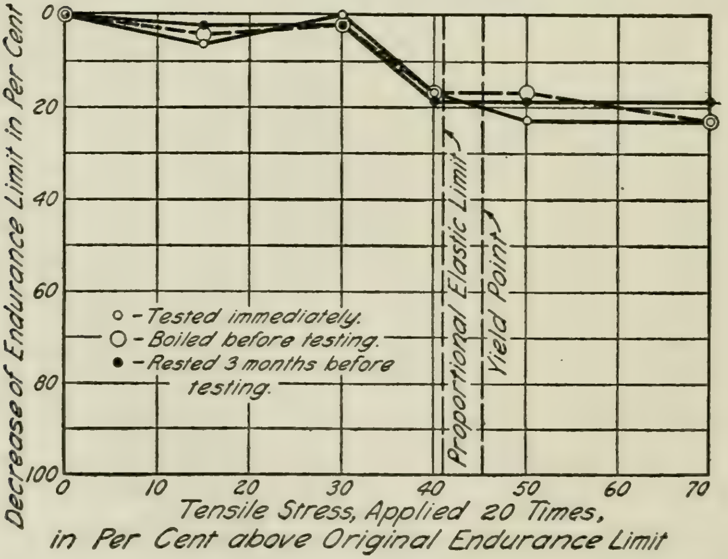

Fig. 14. Diagram Showing Effect on Endurance Limit of Direct Axial Static Stress Applied Twenty Times

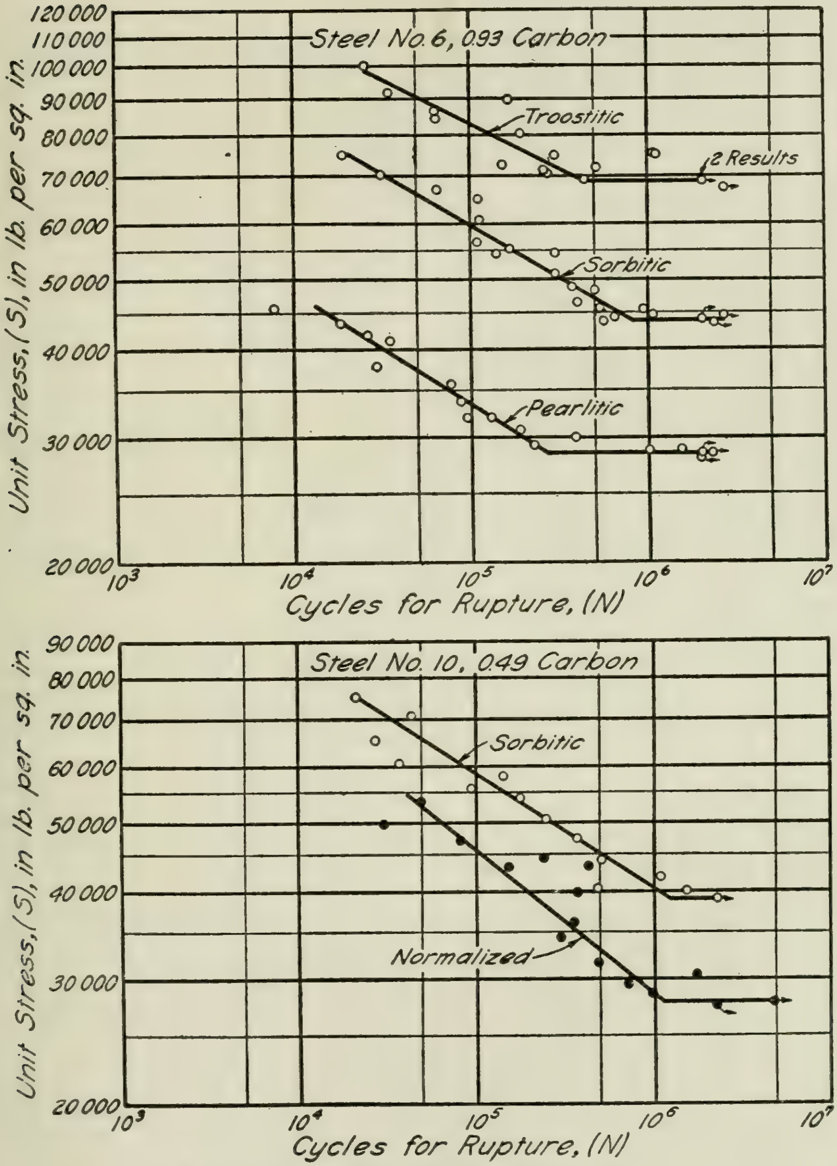

FIG. 15. *S-N* DIAGRAMS FOR 0.93 CARBON STEEL AND 0.49 CARBON STEEL, UPTON-LEWIS REVERSED-BENDING TESTS

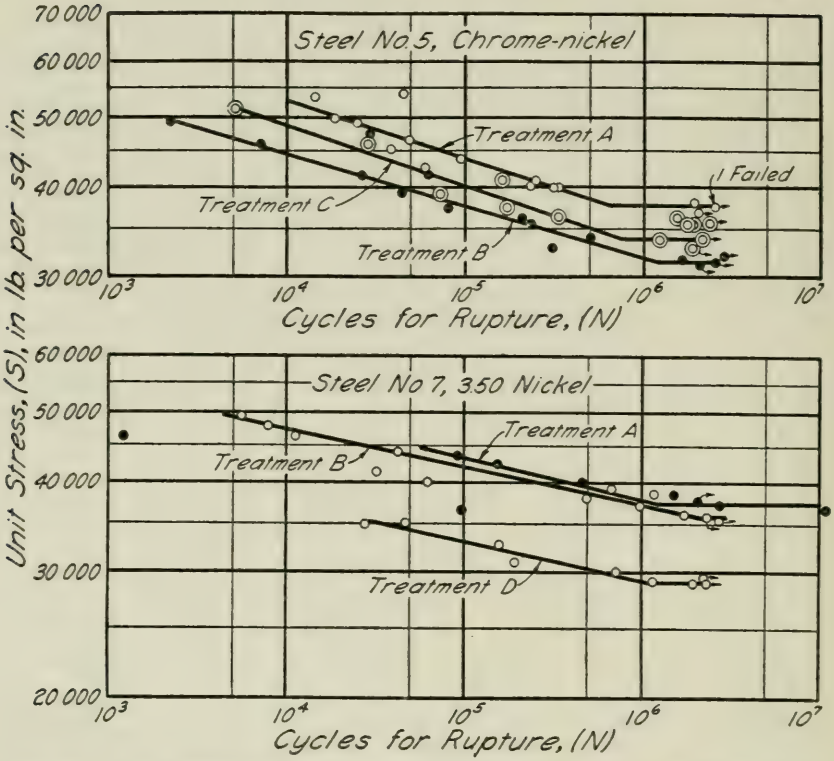

FIG. 16. *S-N* DIAGRAMS FOR CHROME-NICKEL STEEL AND 3.50 NICKEL STEEL, OLSEN-FOSTER REVERSED-TORSION TESTS

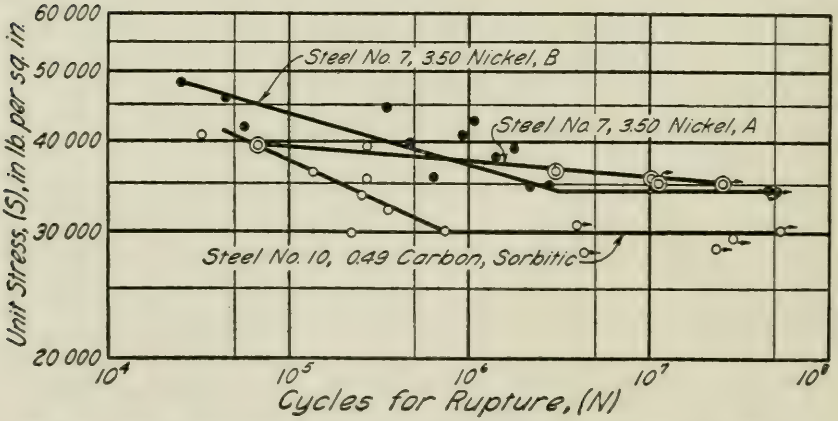

FIG. 17. *S-N* DIAGRAMS FOR 3.50 NICKEL STEEL AND 0.49 CARBON STEEL, ILLINOIS REVERSED-TORSION TESTS

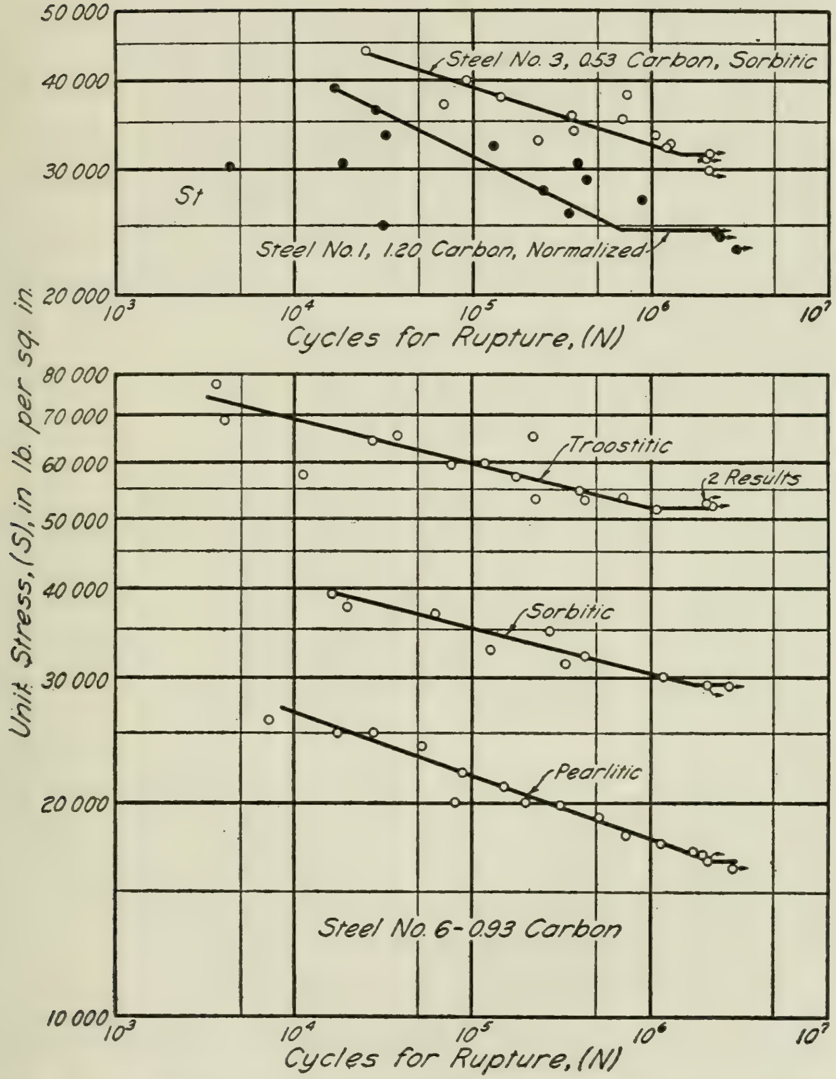

FIG. 18. *S-N* DIAGRAMS FOR 1.20 CARBON STEEL, 0.53 CARBON STEEL, AND 0.93 CARBON STEEL, OLSEN-FOSTER REVERSED-TORSION TESTS

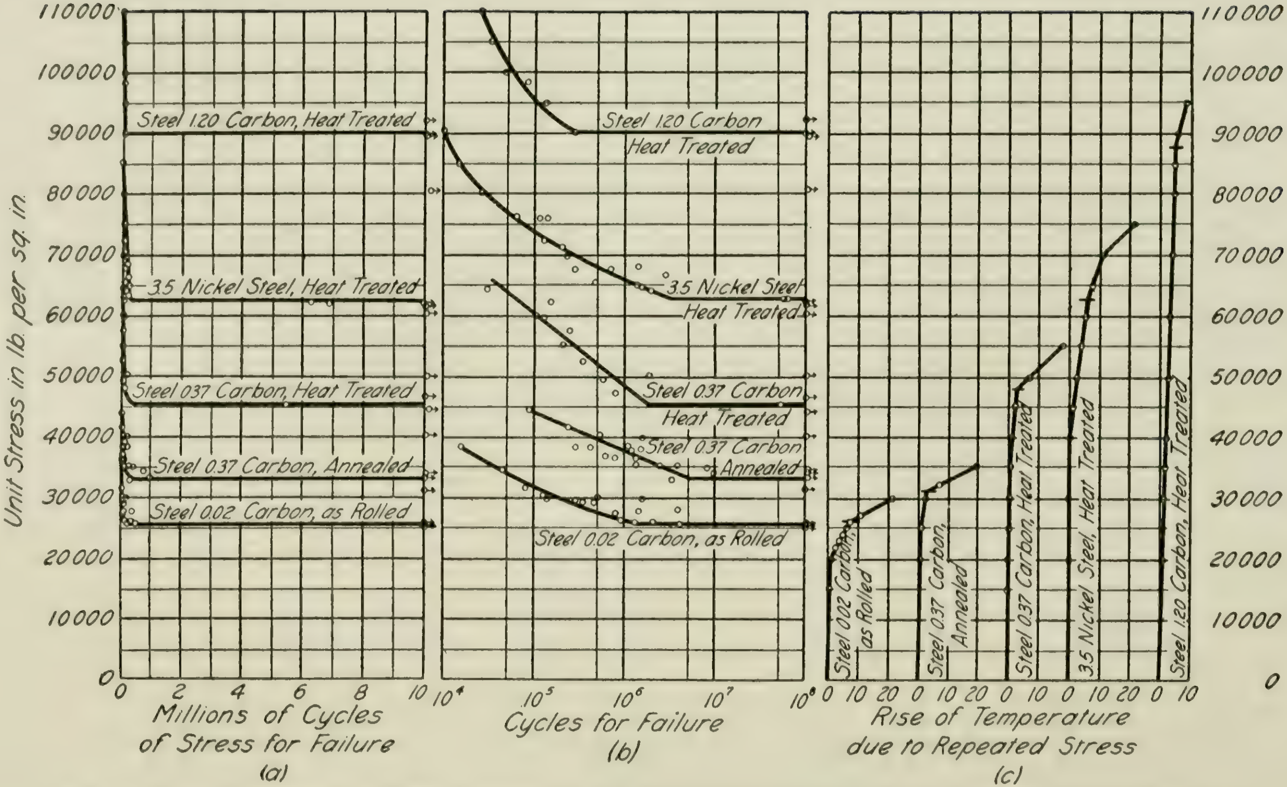

Fig. 19. Typical Cartesian and Semi-Logarithmic S-N Diagrams and Diagrams for Rise-of-Temperature Tests

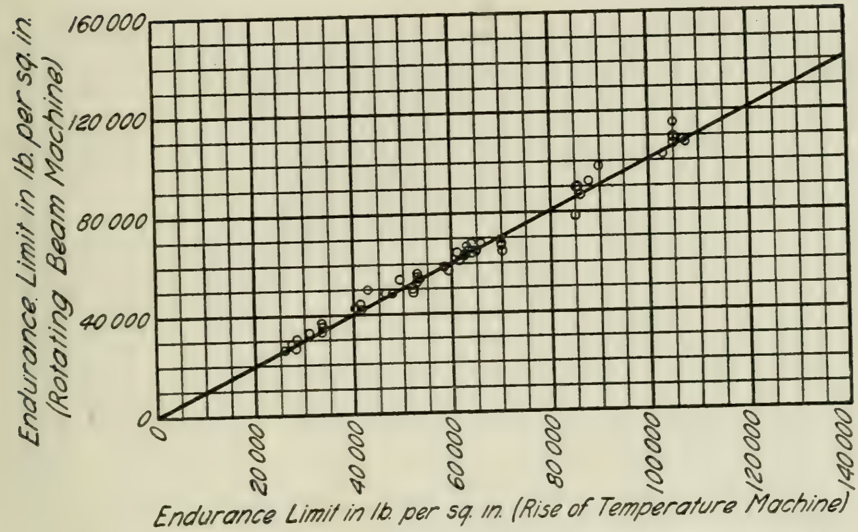

FIG. 20. CORRELATION OF ENDURANCE LIMIT DETERMINED BY ROTATING-BEAM TESTS WITH ENDURANCE LIMIT DETERMINED BY RISE-OF-TEMPERATURE TESTS

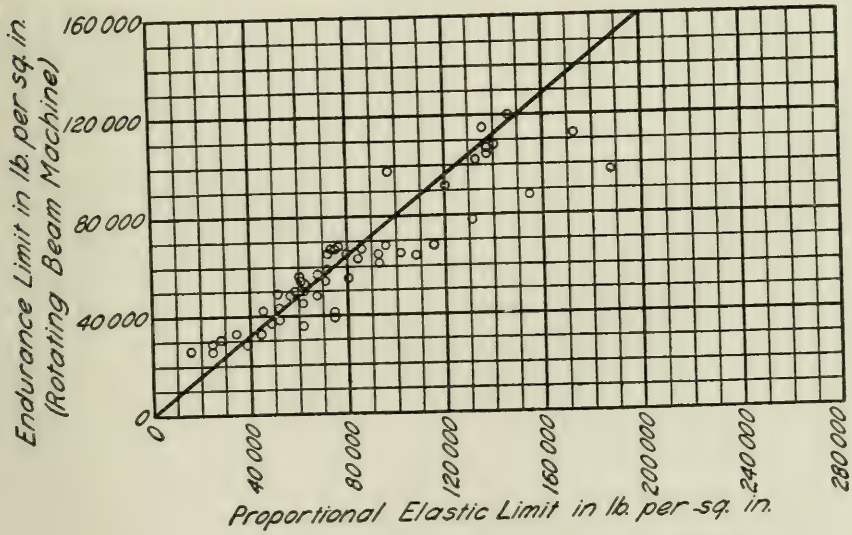

FIG. 21. CORRELATION OF ENDURANCE LIMIT WITH PROPORTIONAL ELASTIC LIMIT (TENSION)

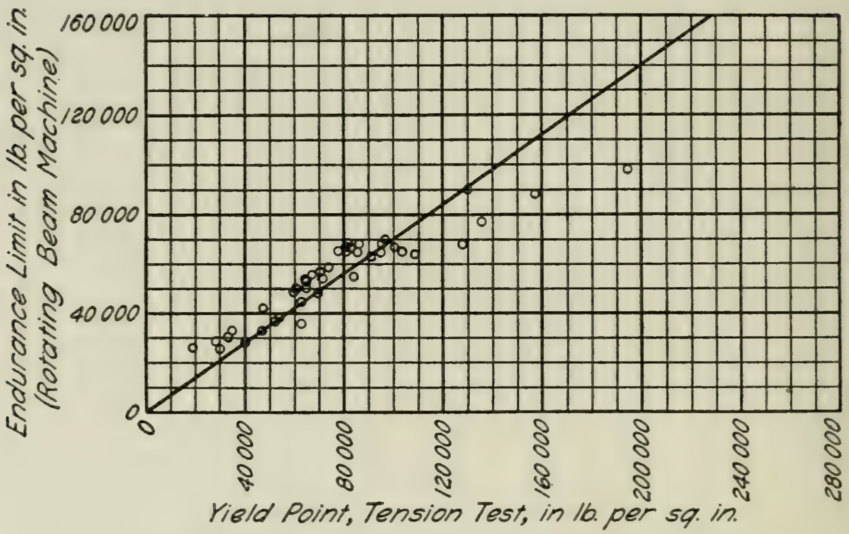

FIG. 22. CORRELATION OF ENDURANCE LIMIT WITH YIELD POINT (TENSION)

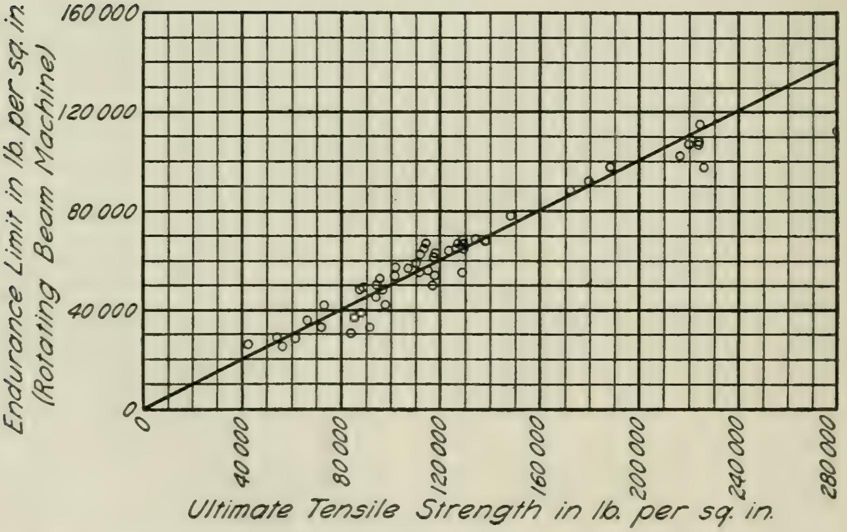

FIG. 23. CORRELATION OF ENDURANCE LIMIT WITH ULTIMATE STRENGTH (TENSION)

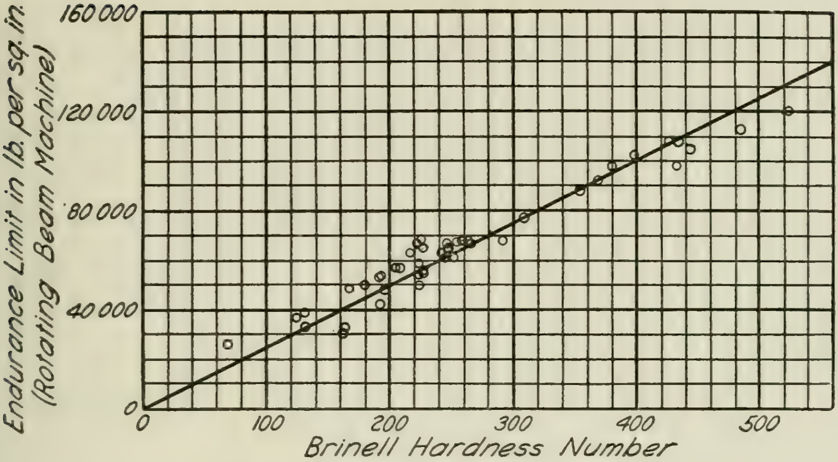

FIG. 24. CORRELATION OF ENDURANCE LIMIT WITH BRINELL HARDNESS

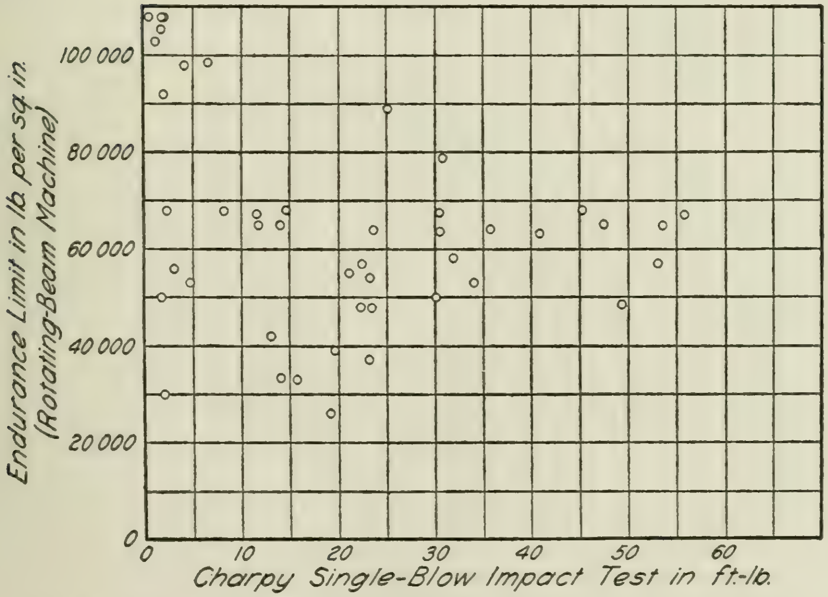

FIG. 25. CORRELATION OF ENDURANCE LIMIT WITH CHARPY IMPACT RESULTS

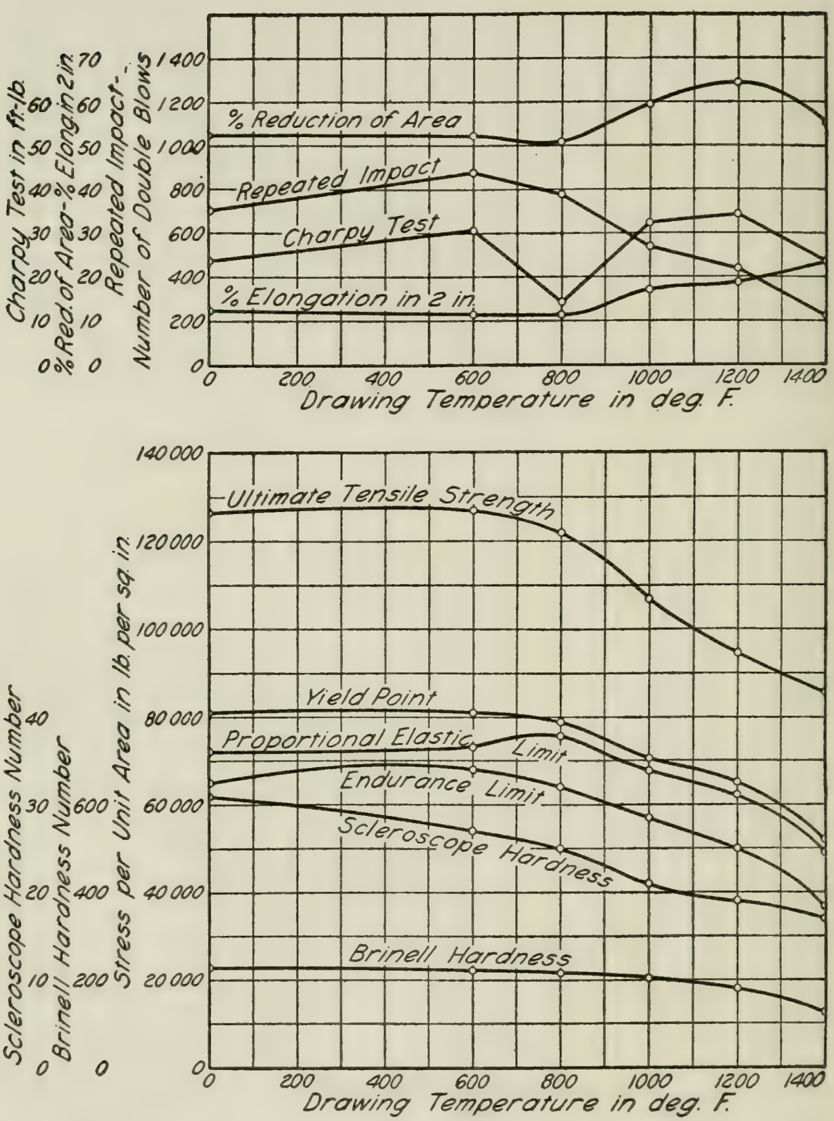

FIG. 26. CURVES SHOWING PHYSICAL PROPERTIES, HEAT-TREATMENT SERIES I, 0.49 CARBON STEEL

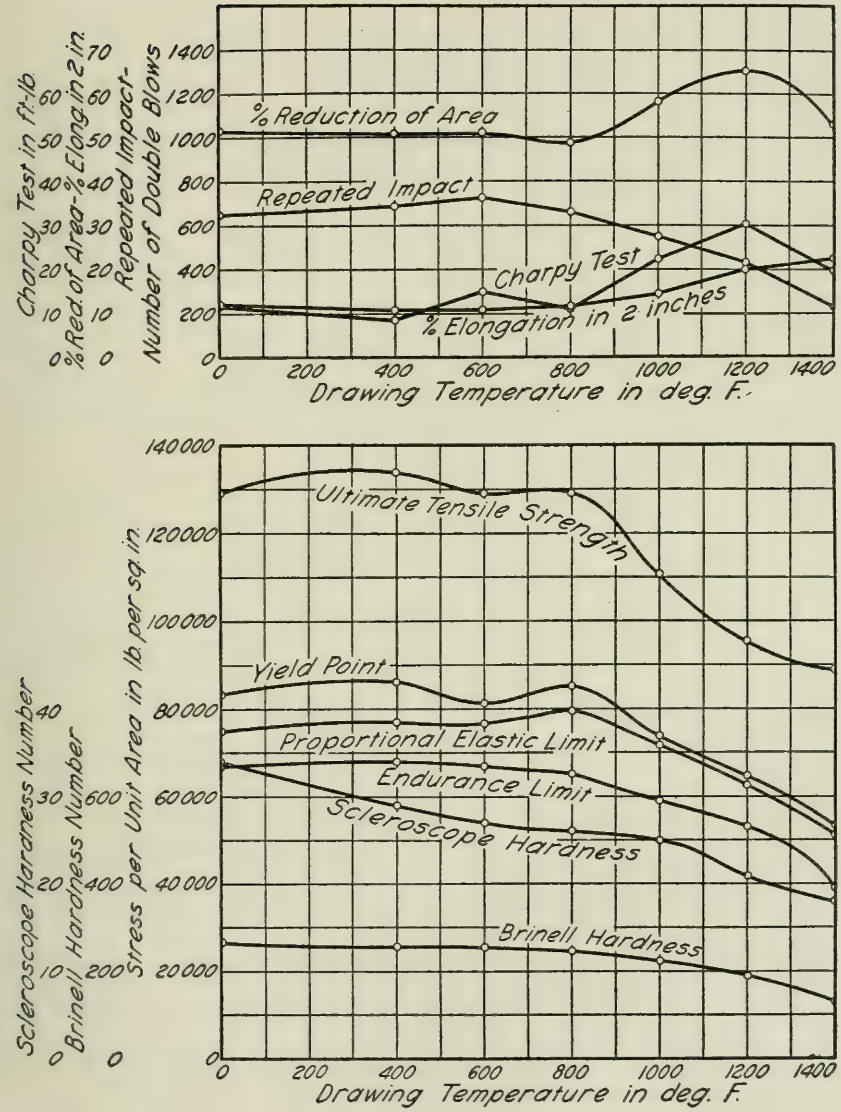

FIG. 27. CURVES SHOWING PHYSICAL PROPERTIES, HEAT-TREATMENT SERIES IA, 0.53 CARBON STEEL

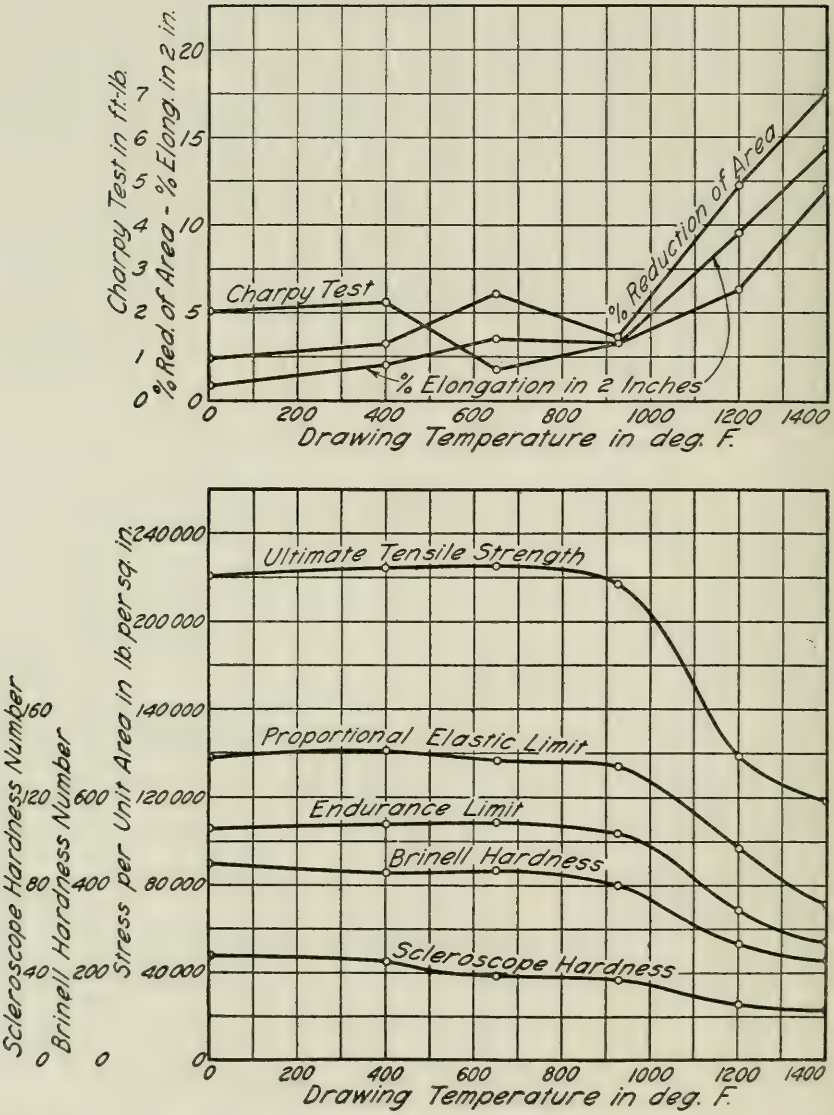

FIG. 28. CURVES SHOWING PHYSICAL PROPERTIES, HEAT-TREATMENT SERIES II, 1.20 CARBON STEEL

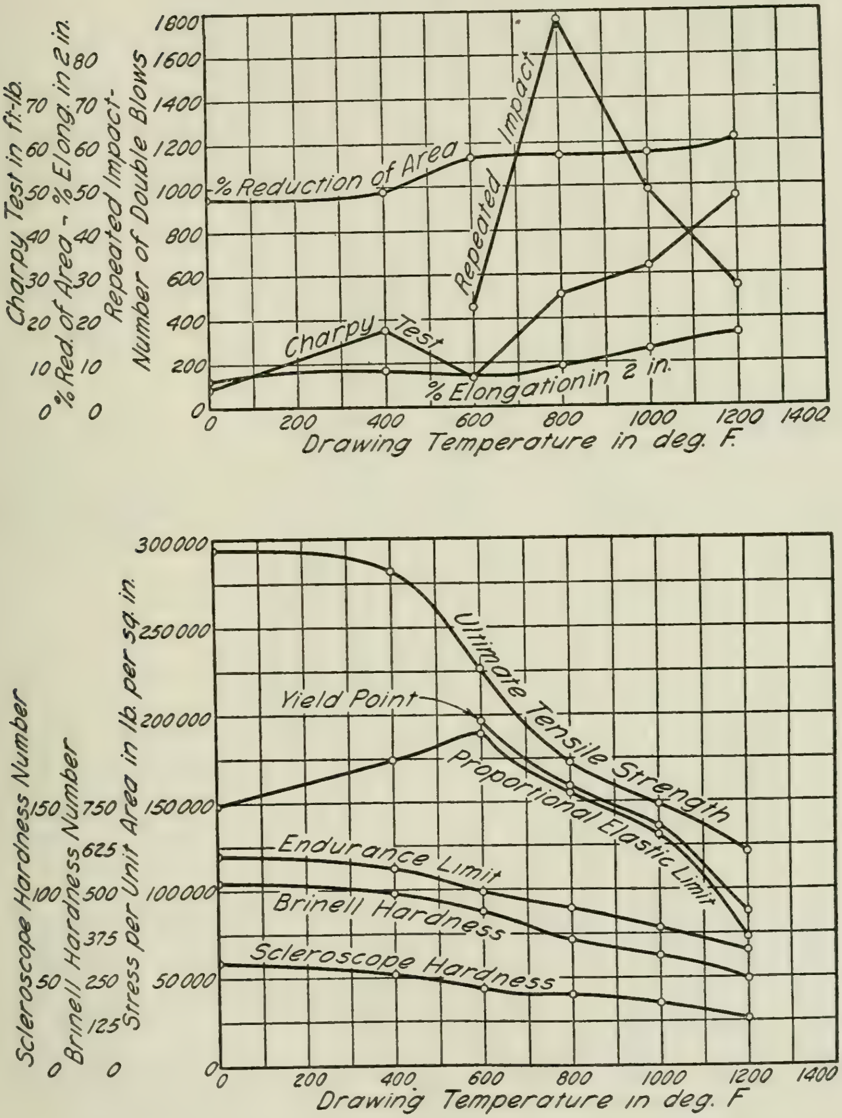

Fig. 29. Curves Showing Physical Properties, Heat-Treatment Series III, 3.50 Nickel Steel

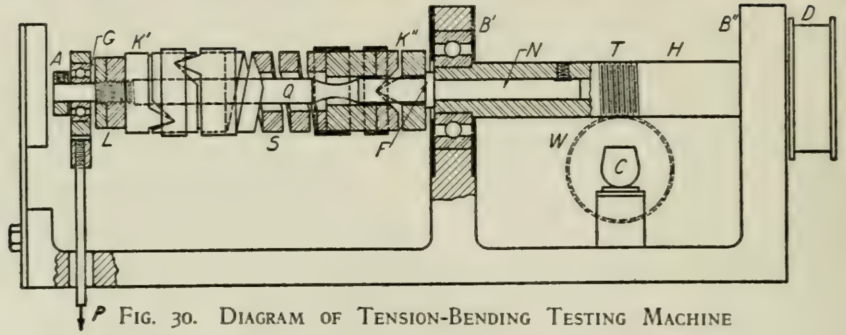

Fig. 30. Diagram of Tension-Bending Testing Machine

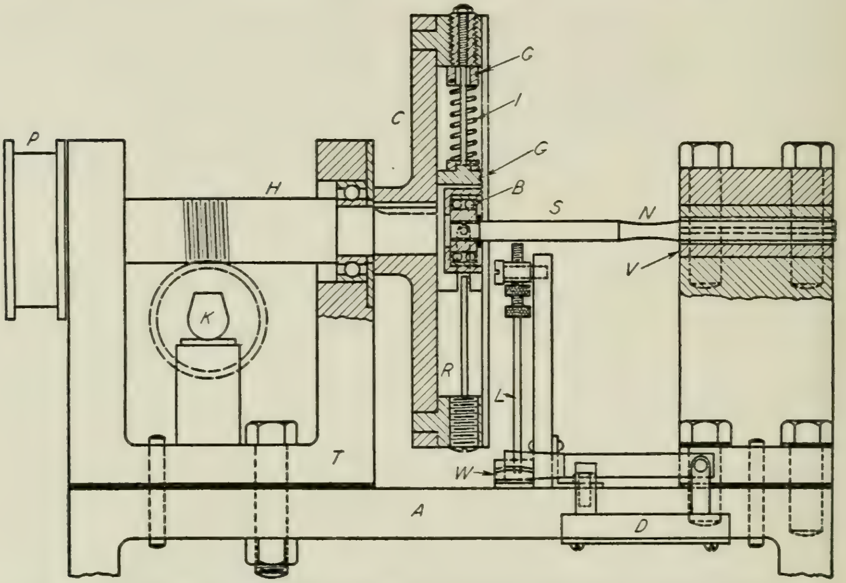

Fig. 33. Diagram of Rotating-Spring Reversed-Bending Testing Machine

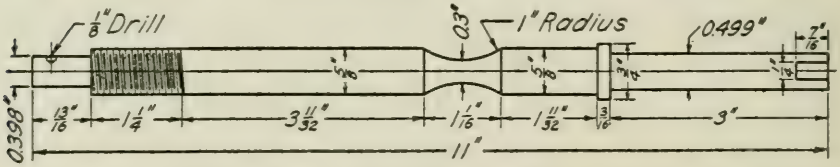

Fig. 31. Test Specimen for Tension-Bending Testing Machine

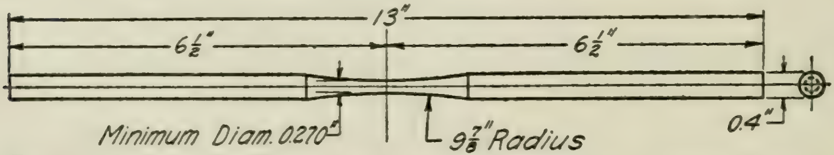

Fig. 32. Specimen for Rotating-Beam Testing Machine (Farmer Type)

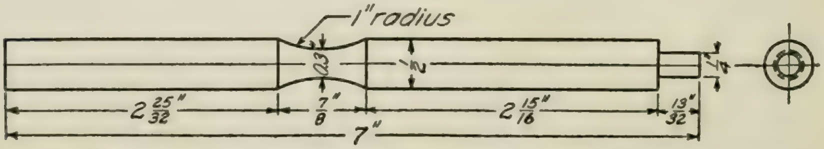

Fig. 34. Specimen for Rotating-Spring Reversed-Bending Testing Machine

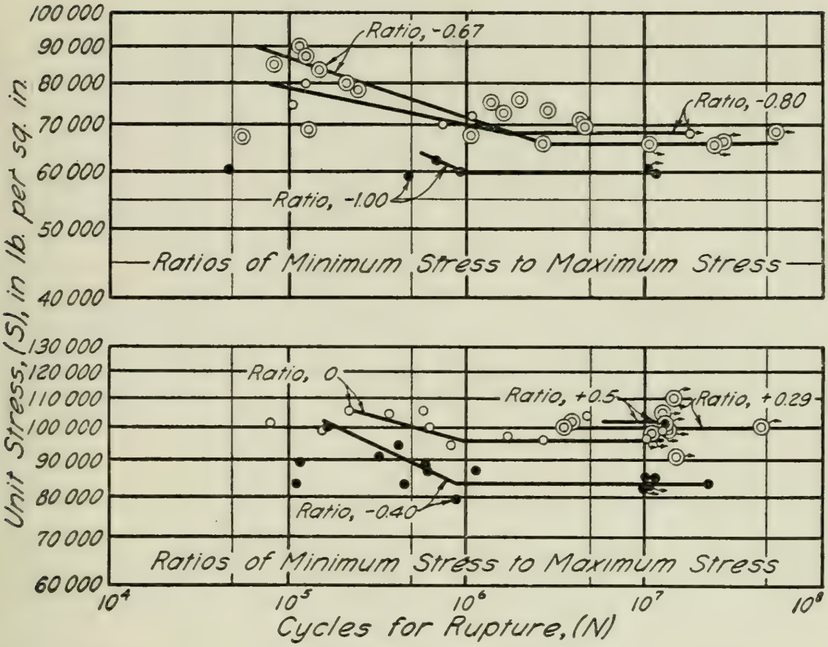

FIG. 35. *S-N* DIAGRAMS FOR 3.50 NICKEL STEEL, TREATMENT A, TENSION-BENDING TESTS

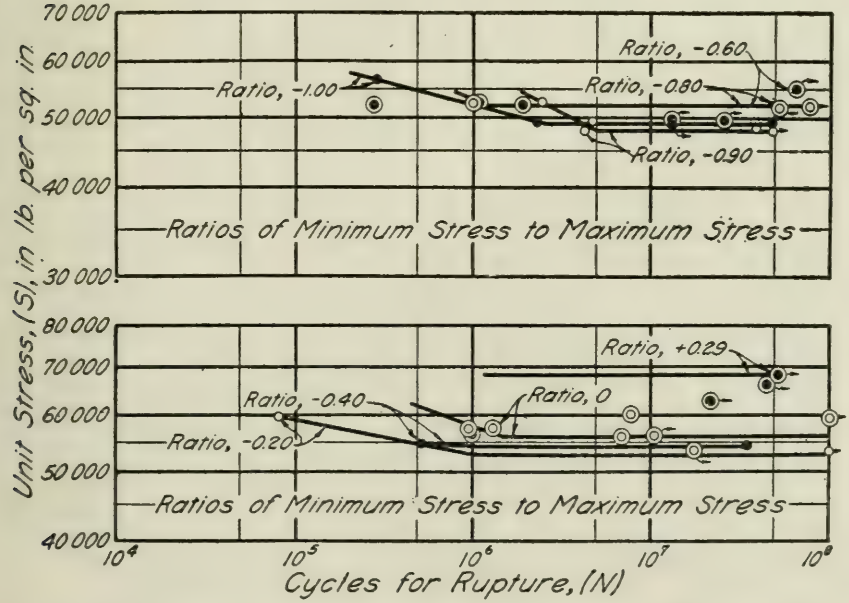

FIG. 36. *S-N* DIAGRAMS FOR 3.50 NICKEL STEEL, TREATMENT D, TENSION-BENDING TESTS

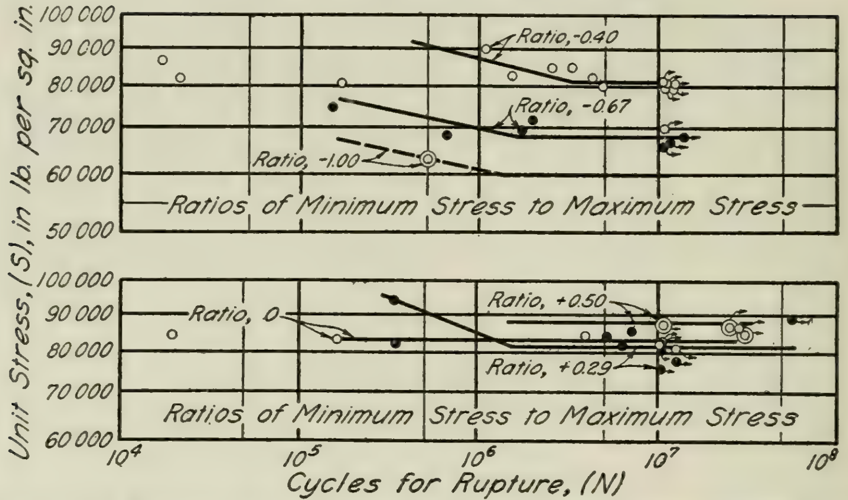

FIG. 37. *S-N* DIAGRAMS FOR 3.50 NICKEL STEEL, TREATMENT B, TENSION-BENDING TESTS

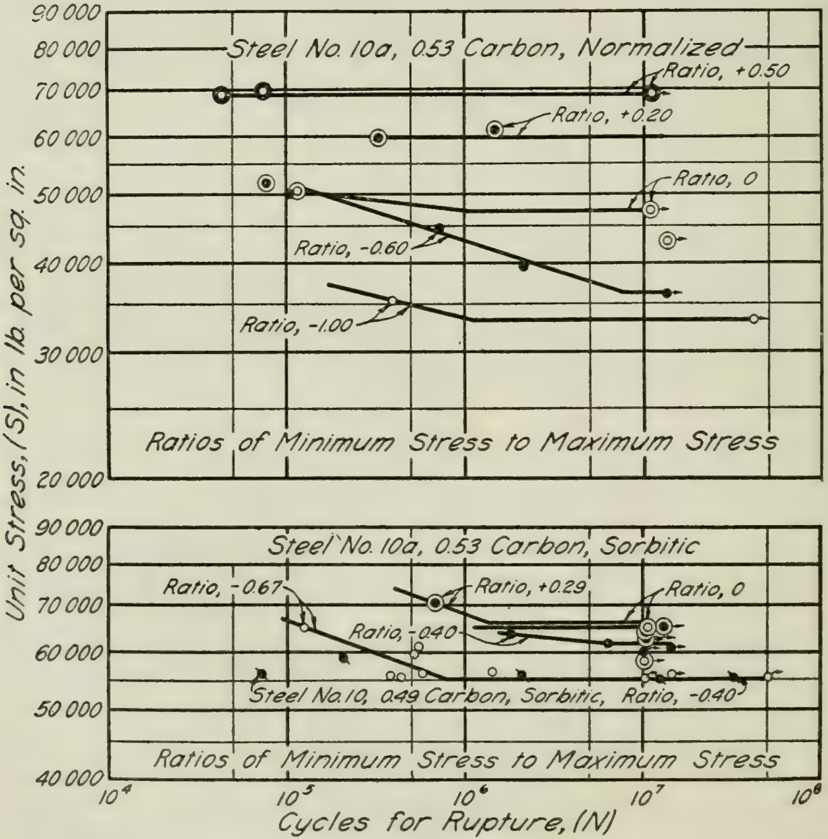

FIG. 38. *S-N* DIAGRAMS FOR 0.53 CARBON STEEL, TENSION-BENDING TESTS

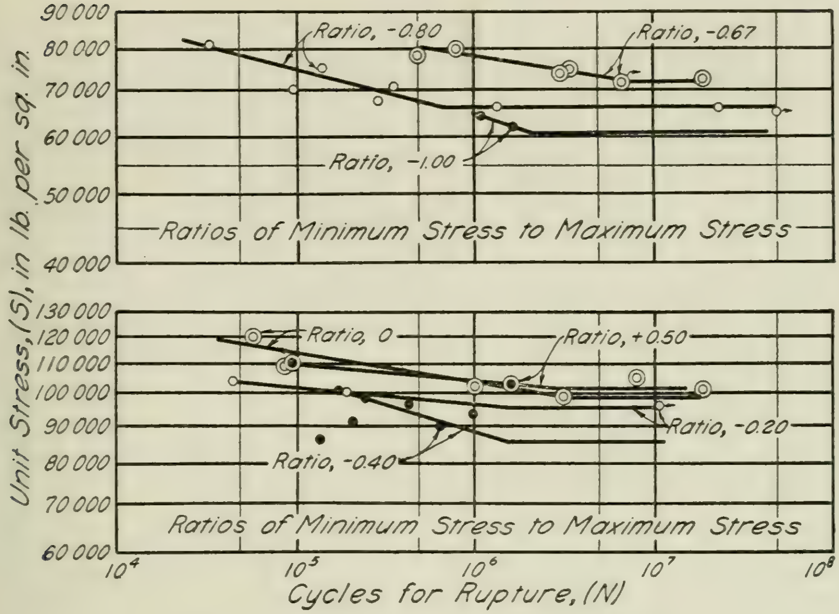

FIG. 39. *S-N* DIAGRAMS FOR 3.50 NICKEL STEEL, TREATMENT C, TENSION-BENDING TESTS

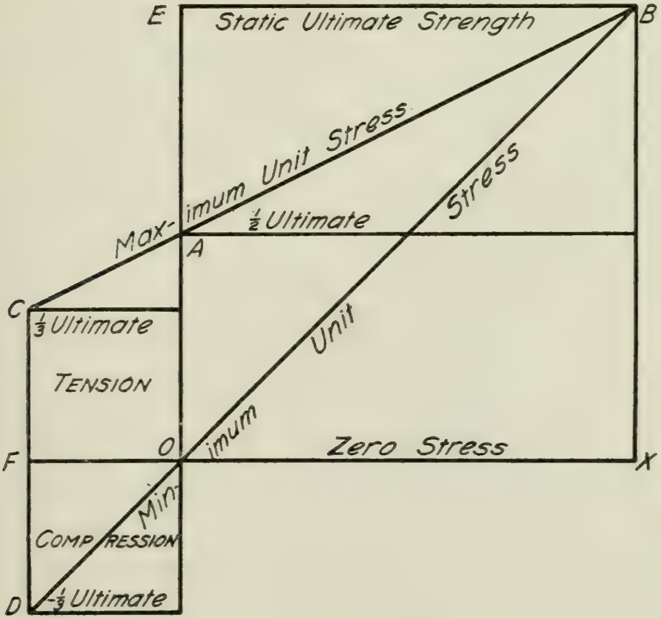

FIG. 40. GOODMAN'S DIAGRAM

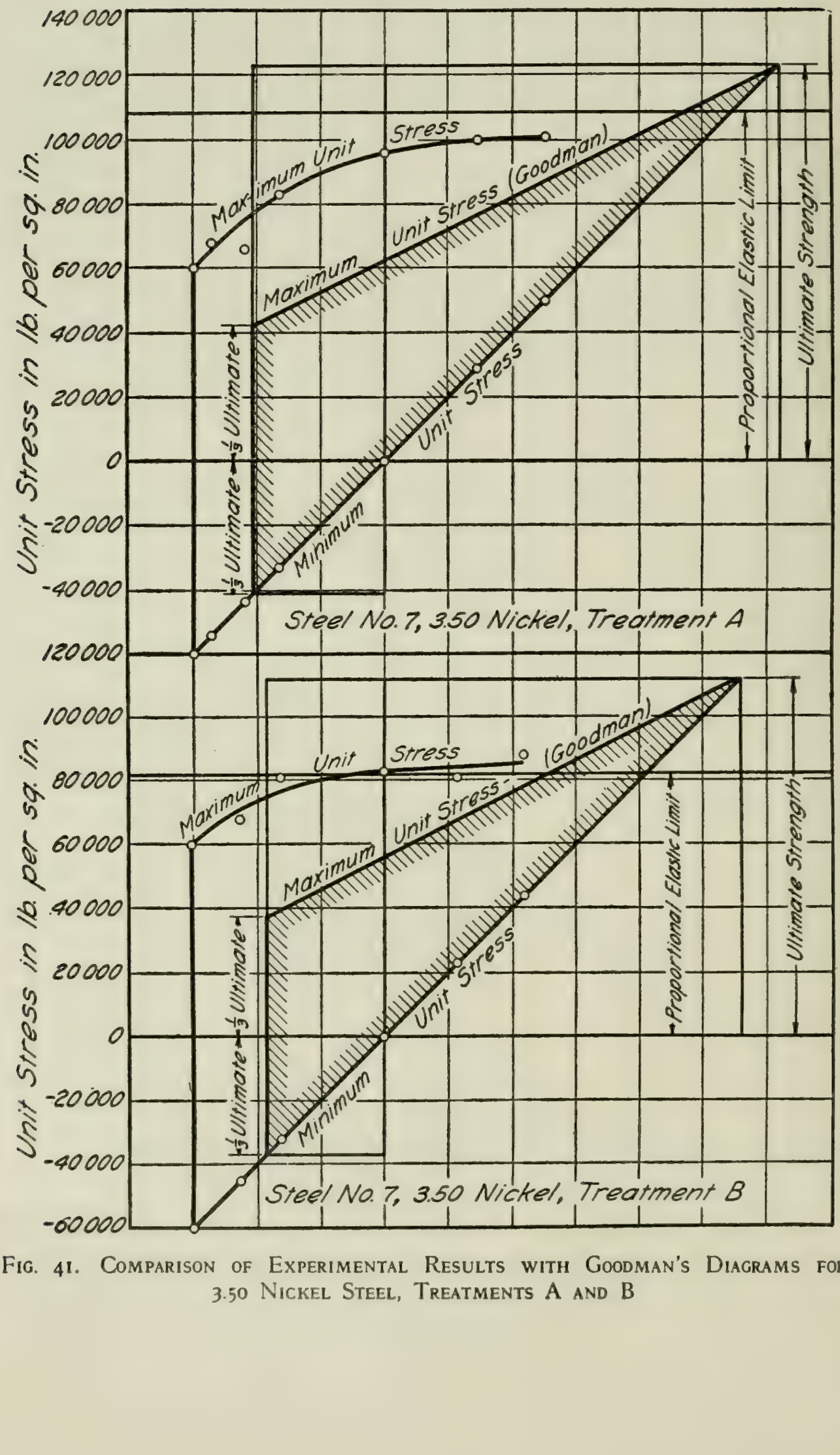

FIG. 41. COMPARISON OF EXPERIMENTAL RESULTS WITH GOODMAN'S DIAGRAMS FOR 3.50 NICKEL STEEL, TREATMENTS A AND B

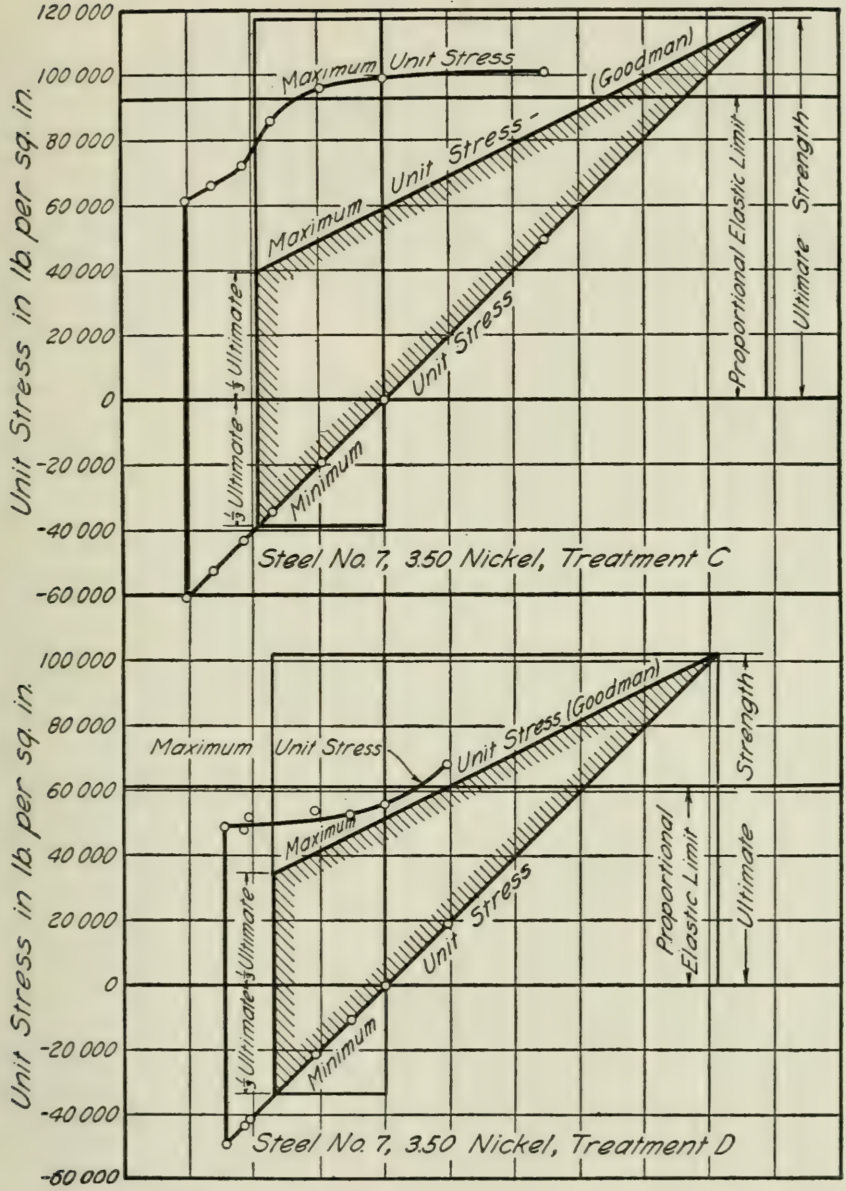

Fig. 42. Comparison of Experimental Results with Goodman's Diagrams for 3.50 Nickel Steel, Treatments C and D

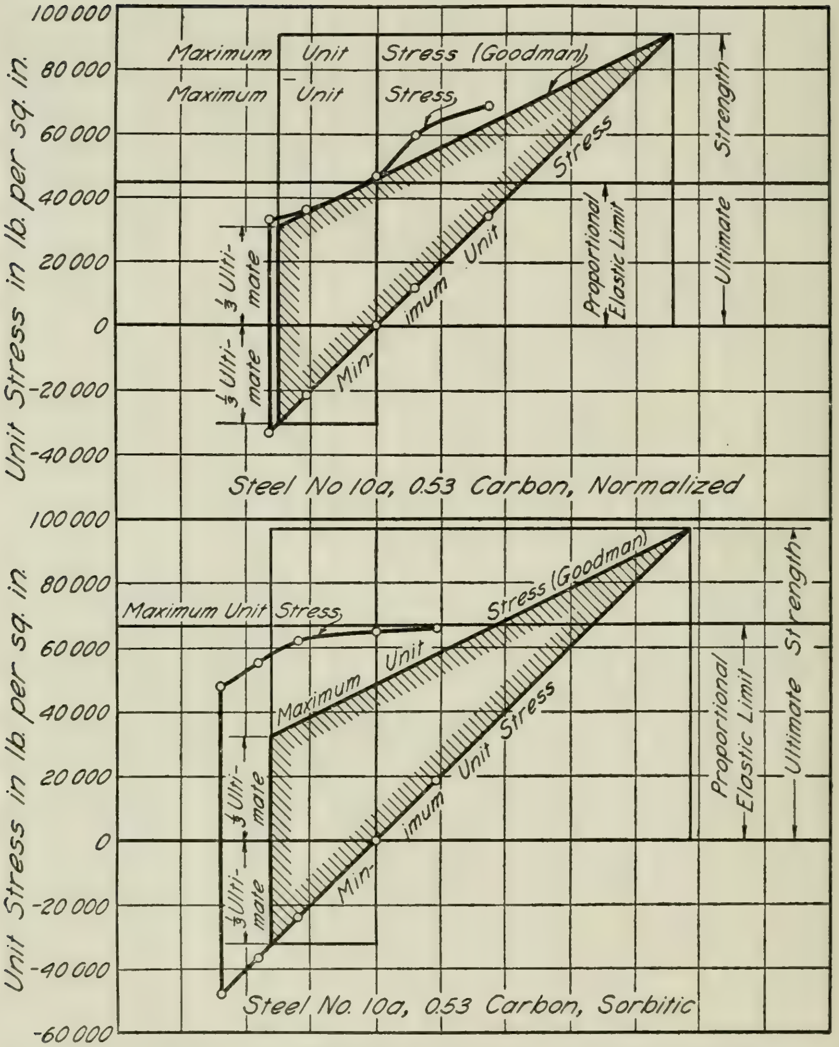

Fig. 43. Comparison of Experimental Results with Goodman's Diagrams for 0.53 Carbon Steel

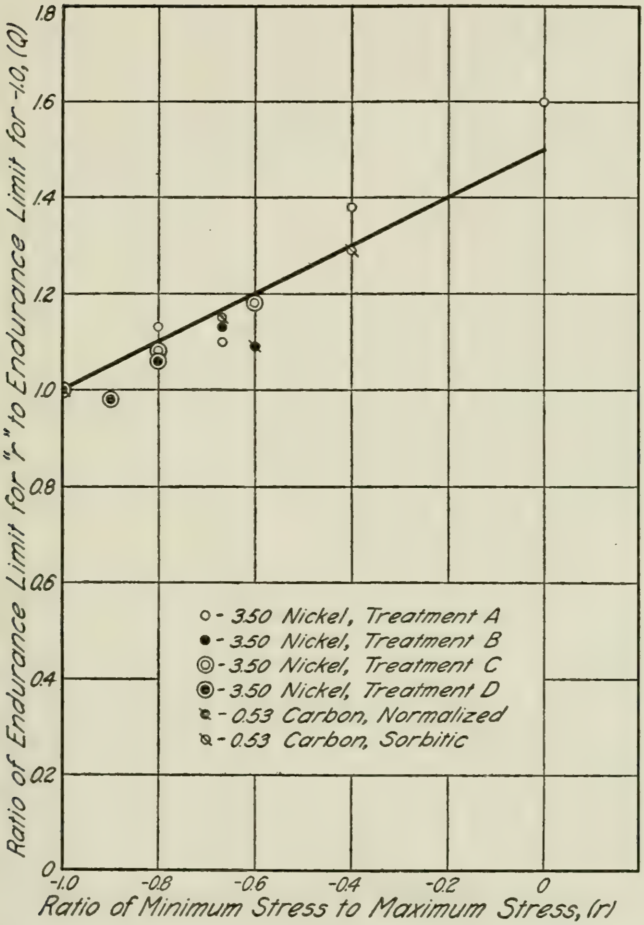

FIG. 44. DIAGRAM SHOWING LIMITING STRESS RATIOS FOR VARIOUS RATIOS OF MINIMUM STRESS TO MAXIMUM STRESS

GLOSSARY OF TECHNICAL TERMS

Alloy Steel.—A steel which owes its characteristic properties chiefly to the presence of an element or elements other than carbon.

Annealing.—See Heat Treatment.

Brinell Test.—See Hardness.

Charpy Test.—See Impact Test.

Compression.—See Deformation.

Constantan.—An alloy of copper and nickel used in thermo-couples.

Cycle of Stress.—See Repeated Stress.

Deformation.—Change of form accompanying the application of external load. The term strain is used in this report as synonymous with deformation. Deformations may be stretches under tension, compression under compressive load, deflections under bending (or flexure), twists under torsional moment, or detrusions under shear. Twist is a special case of shearing detrusion. The deformation per unit of length over any gage length on a specimen is called the unit deformation or unit strain.

Detrusion.—See Deformation.

Draw.—See Heat Treatment.

Ductility.—Ability to withstand stretch without rupture. Ductility is usually measured by the percentage of elongation after rupture over a gage length laid off on a specimen before stretching, or by the reduction of area of the original cross-section of a specimen when tested in tension.

Elastic Limit.—The term is, unfortunately, used very loosely in general practice. In this report the term elastic limit or set elastic limit is used to denote the highest unit stress at which material will completely recover its form after the stress is removed. *Proportional limit,* or proportional elastic limit, is used to denote the highest unit stress at which stress is proportional to deformation. The values found for both elastic limit and proportional limit are dependent on the accuracy of apparatus used and the precision of plotting stress-strain diagrams. For practical purposes elastic limit and proportional limit may be regarded as interchangeable terms. The yield point is that unit stress at which material shows a sudden marked increase in the rate of deformation without increase in load. It is usually determined by the sudden drop in the balance beam of the testing machine as strain is applied to the specimen at a uniform rate, or by a sudden increase of deformation which can be seen by the use of a pair of dividers on the specimen.

Endurance.—The number of cycles of repeated stress withstood by a specimen before failure.

Endurance Limit.—The highest unit stress which, applied in cycles of completely reversed stress, can be withstood an indefinite number of times without failure. If an *S-N* diagram for a series of reversed-stress tests is plotted to logarithmic co-ordinates the endurance limit is the unit stress at which the diagram abruptly changes direction from a sloping line to a horizontal line.

Endurance Strength.—A general term denoting ability to resist repeated stress; synonymous with fatigue strength.

Fatigue.—The action which takes place in material causing failure after a large number of applications of stress. Failures due to fatigue are characterized by their suddenness, and by the absence of general deformation in the piece which fails.

Ferrous Metals.—Metals whose principal ingredient is iron. The common ferrous metals are: wrought iron, cast iron, malleable cast iron, and steel.

Fillet.—A curved surface at the junction of two different sized parts of a member of a structure or machine. The use of a fillet prevents a sharp angle at the junction.

Flaw.—Any defect in metal, either a surface defect or a defect in grain structure.

Hardness.—Is used with a variety of meanings. In this report it is used to denote resistance to penetration. The two common tests for hardness are the Brinell test and the scleroscope test. In the Brinell test a hardened steel ball of a standard diameter is forced against the surface of a test specimen, using a standard pressure. The diameter or the depth of the resulting impression is an inverse measure of the hardness. In the scleroscope test a small weight fitted with a diamond point is allowed to fall from a standard height upon the surface of the specimen, thus causing a minute indentation. The height of rebound is a measure of the hardness.

Heat Treatment.—Of steel is the proper control of heating and cooling so as to produce the desired structure (pearlitic, sorbitic, etc.), and includes:

Annealing.—Which consists in very slow cooling from above the critical range, and which gives a large-grained, soft, pearlitic structure.

Normalizing.—Which consists in cooling from above the critical range in still air and which gives a fine-grained, pearlitic structure.

Oil Quenching.—Which consists in cooling from above the critical range by cooling in oil at room temperature, and which yields steel of sorbitic or troostitic structure, depending on the carbon content (certain special alloy steels yield a martensitic structure or even an austenitic structure with oil quenching).

Water Quenching.—Which consists in cooling from above the critical range by cooling in water at room temperature, and which yields steel of martensitic, troostitic, or sorbitic structure, depending on the carbon content (certain special alloy steels yield a martensitic or an austenitic structure with water quenching).

Drawing.—Which consists in reheating quenched steel to a temperature slightly below the critical range and then cooling. This process tends to bring martensitic, troostitic, or sorbitic steel towards the pearlitic state, and, by varying the temperature of drawing, it is possible to control the state of the steel with a good degree of precision.

Other liquids are sometimes used for quenching steel; such as molten lead, molten barium chloride, ice water, and brine.

Alloying elements, including carbon, retard the transition so that high-carbon steels and alloy steels are more susceptible to heat treatment than are low-carbon steels. See Metallography.

Impact Test.—A test in which a specimen is subjected to a very suddenly applied load. In the machines commonly used for making impact tests of steel specimens the sudden load is applied by the blow of a swinging pendulum. The three machines in common use for this test are the Charpy, the Izod, and the

Olsen. Impact tests in flexure are usually made on small beams of steel with a sharp notch in them, because an unnotched beam would bend without fracturing; such tests being sometimes called notched-bar tests. Impact-tension tests are also sometimes made. In the three machines mentioned enough energy is stored in the raised pendulum to break the specimen with a single blow. Impact tests using repeated blows to fracture the specimen are also made; a well known machine is the Stanton.

Logarithmic Coordinates.—Coordinates for plotting results of tests in which the scale used is proportional to the logarithms of the values plotted.

Metallography.—Metallography deals with the physical state and the proximate constituents of a metal or an alloy. It has to do with the physical grouping, distribution of constituents, and relative dimensions of the substances as revealed by microscopic examination. It may be characterized as a study of the anatomy of metals.

Steel is an alloy the essential constituents of which are iron and carbon, the latter being the controlling element. *Carbon* exists in steel as a carbide of iron, Fe_3C, to which the name cementite is applied. The free iron, or *ferrite,* together with the *cementite,* has the power of forming a conglomerate called *pearlite,* a very intimate mechanical mixture composed of about 7 parts of ferrite to one part of cementite. If molten iron be cooled, there is formed first a solution of carbon in molten iron, then as the metal solidifies the carbon exists as cementite in solid solution in the iron. This solid solution is called *austenite,* and it crystallizes into imperfect crystals or grains. With further cooling the steel passes through a *critical,* or transformation, *range* of temperature (extreme range about 1650 degrees F. to 1250 degrees F.), and the two constituents of the metal pass successively through several transition stages, namely: *martensite,* in which long needle-like crystals are formed, giving a very hard and brittle substance; *troostite,* in which dark colored masses resembling sorbite (see below) are surrounded by a groundwork of martensite, the troostitic state yielding a substance hard but tougher than the martensitic; *sorbite,* in which cementite and ferrite are in a state resembling an emulsion, yielding a substance fairly hard and very tough; and *pearlite,* in which ferrite and cementite exist, usually in stratified layers or bands. If the steel has a carbon content of about 0.90 per cent all the grains will be pearlite; if the carbon content is lower than 0.90 per cent there will be grains of pearlite and grains of ferrite; if the carbon content is greater than about 0.90 per cent there will be grains of pearlite and grains of cementite.

The presence of carbon or of other alloying elements retards the process of transition. By varying the rate of quenching steel the transition process may in general be halted at any desired stage, and the resulting cooled steel may be given any desired characteristic structure. See Heat Treatment.

Non-Ferrous Metals.—Metals in which iron is not a constituent, or is only present in very small quantities.

Pearlite.—See Metallography.

Repeated Stress.—This is the general term used to denote any regular variation of stress applied to a member a large number of times. Repeated stress includes variations in magnitude of stress in one direction, variations from stress in one direction to a smaller stress in the opposite direction, and variations from stress in one direction to equal stress in the opposite direction. This last-named case of repeated stress is called *reversed* or *alternating* stress. In repeated stress the periods of variation are repeated again and again, and each complete period of variation is called a *cycle of stress.* The algebraic difference between the maximum stress and the minimum stress during a cycle of stress is called the *range of stress.*

Shear, Shearing Stress.—See Stress.

S-N Diagram.—A diagram showing the results of a series of repeated stress tests. Values of unit stress are plotted as ordinates, and values of corresponding numbers of cycles of stress to cause failure are plotted as abscissas.

Sorbite.—See Metallography.

Static Test.—A test of a specimen in which the rate of application of load is so slow that it may be regarded as zero. The term refers in general to a test made with an ordinary testing machine.

Steel.—The term steel is used to denote any ferrous metal with a carbon content less than about 1.7 per cent, which is made by a process involving complete fusion. Thus Steel No. 9, which chemically is almost pure iron, and which is called Armco Iron by the manufacturers, is designated as 0.02 carbon steel. *Wrought iron* has a low carbon content, and is made from a pasty mass at a temperature below complete fusion. Ferrous metals with a carbon content higher than about 1.7 per cent are called *cast iron.*

Stress.—An internal force which resists the destructive action of external force. Stresses are always accompanied by strains or deformations. There are tensile stresses, compressive stresses, and shearing stresses. Torsion on a specimen is resisted by shearing stress. At any point on a stressed member the stress per unit area is called the unit stress. Sometimes the term stress is used to denote unit stress.

Ultimate Tensile Strength.—The highest unit stress carried by a tension specimen in a test to rupture. In computing ultimate tensile strength the original area of cross-section of the specimen is used.